TL 481

Draft Translation 481
June 1975

INDICATORS FOR FORECASTING SHIP ICING

AD A030113

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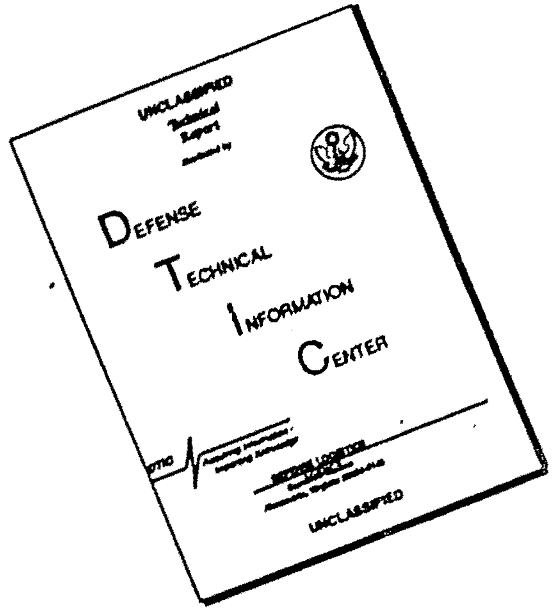
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DRAFT TRANSLATION 481	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): INDICATORS FOR FORECASTING SHIP ICING	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Ye.P. Borisenkov and I.G. Pchelko, eds.	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE: June 1975
	13. NUMBER OF PAGES: 60
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

METEOROLOGICAL FACTORS
SHIP ICING
ICE FORMATION INDICATORS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

received

The USSR Hydrometeorological Center has twice published "Tentative Instructions on Warning Of A Possible Icing of Ships" (in 1967 and 1969) and each time, the the instructions were subjected to verification under the conditions of the actual operation of the forecasting agencies of our service. In all for the four cold seasons, ~~we received at~~ the USSR Hydrometeorological Center more than 3,000 questionnaires concerning the icing of ships. ~~At a number of establishments in~~ the Hydrometeorological Service, ~~we~~ also collected and

collated the observational data concerning the icing of ships. On the basis of the data indicated above, ~~we published~~ the third ~~of~~ "Procedural Instructions"*. By comparison with the previous publications of "Tentative Instructions", this version has been considerably revised and supplemented. The section on estimating the wave action which was included in this second publication has now been eliminated since in the recommendations given on the estimation and prediction of icing, wave action has been disregarded.

*was published

CRREL-TL-481

DRAFT TRANSLATION 481

ENGLISH TITLE: INDICATORS FOR FORECASTING SHIP ICING

FOREIGN TITLE: (METODICHESKIE UKAZANIIA PO PREDUPREZHDENIIU UGROZY OBLEDENENIIA SUDOV)

EDITORS: Ye. P. Borisenkov ~~and~~ I.G. Pchelko

SOURCE: Glavnoye upravleniye gidrometeorologicheskoy sluzh-by pri sovete ministrov SSSR ~~(Main administration of~~ hydrometeorological service under USSR Council of ~~Ministers)~~. Arctic and Antarctic Scientific-Research Institute (AANII) ~~, Leningrad, 1972, 98lp.~~

CRREL BIBLIOGRAPHY
ACCESSIONING NO. : 27-1072

Translated by U.S. Joint Publications Research Service for U.S. Army Cold Regions Research and Engineering Laboratory, 1975, 60p.

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INDICATORS FOR FORECASTING SHIP ICING

GLAVNOYE UPRAVLENIYE GIDROMETEOROLOGICHESKOY SLUZHBY PRI SOVETE MINISTROV SSSR (Main Administration of Hydrometeorological Service Under USSR Council of Ministers). Arctic and Antarctic Scientific-Research Institute (AANII), Leningrad, 1972, 981 p.

Edited by Dr of Physico-Mathematical Sciences Ye.P. Borisenkov and Dr of Geographic Sciences I. G. Pchelko

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Preface

The USSR Hydrometeorological Center has twice published "Tentative Instructions On Warning Of A Possible Icing Of Ships" (in 1967 and 1969) and each time, the instructions were subjected to verification under the conditions of the actual operation of the forecasting agencies of our service.

From 1967-1971, we conducted the preparation, distribution, collection and collation of questionnaires for special observations of the icing of ships, the preparation of instructions and programs for the automated processing of observational materials, instructions and handbooks on observing the icing of ships, on determining the adhesion of ice and its physical-mechanical properties, on the forecasting and storm warning of icing conditions, etc.

In all for the four cold seasons, we received at the USSR Hydrometeorological Center more than 3,000 questionnaires concerning the icing of ships. At a number of establishments in the Hydrometeorological Service, we also collected and collated the observational data concerning the icing of ships.

As a whole, the collected material makes it possible for the meteorologists-forecasters to study both the physical nature of the actual phenomenon and also the synoptic conditions of its origin. To a considerable extent this was also promoted by the results of laboratory tests and full-scale investigations at sea by an expedition specially organized by the Ministry of Fisheries Economy for this specific purpose.

On the basis of the data indicated above, we published the third edition of "Procedural Instructions". By comparison with the previous publications of "Tentative Instructions", this version has been considerably revised and supplemented. The section on estimating the wave action which was included in this second publication has now been eliminated since in the recommendations given on the estimation and prediction of icing, wave action has been disregarded.

The present "Procedural Instructions" have been compiled by Junior Scientific Staff Member at the USSR Hydrometeorological Center G.V. Vasil'yeva, Senior Scientific Staff Member at the Arctic and Antarctic Scientific Research Institute, V.V. Panov and the Chief Meteorologist at the USSR Ministry of Fisheries A.P. Tyurin.

The section "Mathematical Techniques for Estimating the Intensity of Ships Icing" was compiled by L. G. Kachurin, L. I. Gashin and I. A. Smirnov (State Hydrological Observatory and Leningrad Hydrometeorological Institute), A. P. Tyurin (USSR Ministry of Fish. Economy, Ye. P. Borisenkov and V. V. Panov (Arctic and Antarctic Scientific Research Institute).

Arctic and Antarctic Institute

Part 1. Hydrometeorological Conditions In The Icing Of Ships

Section 1. General Description of Hydrometeorological Conditions Involved In The Icing of Ships

The mariners and specialists in the operating agencies in the hydrometeorological service supporting the fisheries industry and the merchant marine know well that in the northern temperant latitudes, during the winter accompanied by strong winds and negative air temperatures, the icing of ships takes place.

We differentiate three types of icing:

a.) Icing developing during the spraying and flooding of a ship by sea water as a result of strong wind and wave action during negative air temperature;

b.) Icing from a falling of supercooled precipitation, i.e. rain, drizzle or wet snow and also from the falling of supercooled water particles on a ship during the fogging or evaporation of the sea (fresh-water icing);

c.) Mixed icing which forms during a combination of the first and second types of icing

The icing caused by the flooding and spraying of sea water occurs most often.

During the passage of a ship, from the impacts of the hull on a wave, spray forms, settling and freezing on the ship if the air temperature is negative. During a strong wind and severe swell, simultaneously with the spraying of the ship, there occurs the flooding of the deck by water which flows overboard through the storm ports and scuppers. Some of the water will remain on deck and freeze. During this icing, there occurs the depositing of ice on the sides of the ship, deck, rigging, mast and spars, front and side walls of the superstructures.

As a rule, the critical height of the icing structures on a ship depends on wind speed and height of waves. The stronger the wind and the higher the wave height, the higher the sea water spray will fly and hence the higher the icing will extend. The shrouds and stays acquire the shape of cones, gradually converging toward the top.

As a result of the falling of supercooled precipitation s (rain, drizzle or wet snow) and the "smoking" of the sea, fresh ice is formed. Therefore even slight negative air temperatures (of about -1°, -5°) are sufficient to begin the icing of a ship. The falling of supercooled precipitation leads to a more uniform icing of all parts of the ship, including the icing of the high structures: masts, antennas, radar (sonar) masts, and so forth.

The depositing of a large quantity of ice on a ship during the precipitation of supercooled moisture, fog and steaming of the sea occurs when the ship is cruising for a extended time in the icing zone. However intensive icing of marine vessels merely from supercooled precipitation, fog and sea steaming is normally relatively rare. The combination of the first and second types of icing leads to an increase in the rate of the ice's accretion on the ship.

The full-scale (natural) investigations of ship icing conducted in the Sea of Japan, Barents Sea and Baltic Sea in winter of 1967-68, 1968-69, 1969-70 and 1970-71 permitted us to establish the hydrometeorological conditions causing various

degrees of intensity in the icing of fishing vessels, particularly the ships of the MFT type (medium fishing trawler) and of ships similar to it in dimensions and displacement.

During the conditions of the spraying of a ship by sea water (the appropriate wind speed, wave action and ship heading) and earth temperature ranging from 0 to (? number not legible in source), the icing of a ship is minor. On the main deck of the medium fishing trawler, there form only ice crystals which in 2-5 minutes cover 40-50% of the sprayed portion of the deck. By the next spraying, the crystals are washed off but then they accrete once again. At relatively weak wind (7-10 m/sec) and air temperatures below -3°, the bow part of the ship becomes iced to a greater extent. The remaining parts ice over weakly, or are not subjected to icing at all [8, 10].

In the case of a very strong wind (15-25 m/sec) and low air temperature (to -15°), there become coated with ice the main deck, rigging, mast and spars, bow companion-way, and bridgewing. The maximum amount of ice becomes deposited on the main deck and the trawling winch. The upper bridge and the boat deck become glazed very little. The ship stern does not become iced even when the heading is downwind.

The distribution of the amount of ice on different parts of a ship exposed to spray-type icing occurs extremely erratically. The studies conducted from January-February 1968 in Barents Sea on the MFT "Professor Somov" made it possible to establish the following pattern in ice distribution on various surfaces of a ship. On the horizontal surfaces during the various experiments, there was deposited from 30-70% of the ice; on the vertical surfaces, 15-40% of the ice was deposited; on the surfaces with a complex configuration (instruments and mechanisms, 5-30% was deposited; and on the round surfaces (mast and spars and rigging), from 0-30% of the total amount of ice on the ship was deposited.

As soon as the spraying of a ship begins at air temperature below -3°, there will occur immediately the accretion of ice on the metal parts of the ship, i.e. the rail, sides, companion-way, superstructure, stays, etc. Simultaneously ice also accretes on the canvas covers of the windlass, capstan, bilge hatches and sweeping winch. On the main deck which is plated with

wood, at the outset of icing, ice does not form but only slush appears, mixed with sea water, which flows overboard through the storm portholes and the scuppers. At air temperature of -10, -15°, within 1-1.5 hours, the slush changes to white unconsolidated ice and at air temperature of -4, -9°, it freezes within 1.5-2 hours [8, 10].

The ice forming on the metal parts of the ship and on the canvas covers at air temperature to -15° during the first 1.5 - 2 hours after the beginning of icing is very loose, can easily be knocked off and scraped. Subsequently there occurs a hardening of the ice and its permanent adhesion to the ship structures. Ice sticks very tightly with a wooden deck. The hardened ice has a glazed surface and is difficult to chip off [10]. This circumstance is important to consider and one should begin combating the icing immediately after the appearance of ice, without allowing it to achieve great strength.

At the present time, on ships in the fishing fleet and in the fishing kolkhozes for combating the icing of ships we utilize mainly a manual set of tools for chipping the ice; pickaxes, bars, scrapers, and wooden mallets. Wide use is made of the technique of removing the fishing vessels from the dangerous zone, i.e. movement to the shelter of shore, putting in at ports, transfer to a warm current zone, or entry into a broken ice field. However extensive tasks are under way in the development of effective means and methods of combating the icing of ships; their adoption will permit the achievement of navigation and fishing operations in the regions of intensive icing [11].

To a considerable extent, the force of ice's adhesion depends on the nature of the freezing surface. It turned out that the sticking of ice to the wooden and metal deck plates and covers depends mainly on the physical-chemical and mechanical properties of the material, on the air temperature which the freezing is occuring and on the water's salinity. The shear strength of ice adhesion with a wooden plate equals 6.2 kg/cm^2 while the cleavage strength is 3.2 kg/cm^2 at temperature at -5° and 7.2, and 4.0 kg/cm^2 at temperature of -10° [9].

The utilization of epoxy lacquer and organosilicate lacquer for painting a wooden plate permitted us to reduce the freezing of ice to the plate by 3-5 times. The presence of brine reduces appreciably the ice's adhesive force with the cover's surface.

Currently work is being conducted actively on seeking various types of materials or coatings capable of significantly reducing adhesion. There is a basis for considering that in the future the fishing vessels will obtain good coatings protecting them against severe icing [9].

Section 2. Risk Of Ship Icing

Icing presents a specific danger for the fishing vessels having a low freeboard. During a winter storm or hurricane, these ships are exposed to heavy spray and flooding by sea water; as a result, there occurs their intensive icing. Among those vessels which throughout the winter ply their trade in the northern, western and Far Eastern seas, we include: the medium fishing seiners RS 300 (length around 30m, displacement 200-240 tons, 12-man crew), oceangoing seiners SO (length around 29m, displacement 203 tons, 14-man crew), medium fishing trawlers of type SRT (length around 40m, displacement 430-460 tons, 25-26 man crew), and medium refrigerating fishing trawlers SRTR of the "Okean" and "Bologoye" types (length 43-51m, displacement 532-726 tons).

On the Sea of Azov, Black and Caspian Seas, during the winter we perform fishing using medium Black Sea seiners, SCHS and the Sea of Azov-Black Sea seiners ACHS-150 (length 22-25m, displacement 101-117 tons, 10-12 man crew) and also the large BCHS Black Sea seiners (length 26m, displacement 102 tons, 12-man crew).

For the types of ships listed, icing represents a serious threat when air temperature has fallen below -5° and wind speed is 10-15m/sec. At air temperature at -12, -15° and wind speed exceeding 20m/sec, icing is also very hazardous for the larger fishing vessels such as the type RT fishing trawlers (length 58-73m, displacement 1156-1309 tons), the medium fishing refrigerating trawlers, SRTM, of the "Mayak" type (length 54m, displacement 902 tons) and even the large BMRT refrigerator trawlers of the following types: "Mayakovskiy", "Leskov", "Pushkin" (length 87-90m, displacement 3600-3750 tons).

The danger of intensive icing on the fishing ships with low freeboard is found not only in the fact that during the icing period, these vessels receive on the deck, rigging and sparring a large amount of ice, but also in the fact that, owing to the icing of the high parts of the ship (guyropes, masts, stays, antennas, etc), there occurs a considerable elevation in the ship's CG; this could lead to a loss by the ship of its stability, a sudden tipping and sinking.

Thus, as a result of icing in the Norwegian Sea on 26 January 1966, the British fishing trawlers "Lorella" and "Roderigo" were lost. In January 1968, there took place the tragic sinking of three more British fishing trawlers "Saint-Romanus", "Kingston Peridot" Ross Cleveland, and 59 British fishermen.

On 19 January 1965 in the eastern sector of the Bering Sea, four Soviet medium fishing trawlers of type SRT "Sevak", "Sebezh", "Nakhichevan'", "Boksitogorsk" sank.

From 1963-1967 just in the region of the Kuril Islands and Tatarskiy Proliv (Strait) as a result of icing, 19 Japanese ships and 296 Japanese fishermen were lost. The capsizing of ships from icing as a rule takes place suddenly; as a result, in most cases the crews are lost along with the ships [13].

The studies conducted in winter of 1967-68 and 1968-69 in the Sea of Japan on the MFT "Akademik Ber" demonstrated that the greatest frequency of the spraying of ships during identical hydrometeorological conditions occurs when the ships are heading into the wind at angles of 15-45°. In case of a vessel heading strictly into the wind, the frequency of spraying enhance also the icing intensity, decrease somewhat [6, 10]. In this case, there occurs a uniform icing, while at angles to the wind direction, an asymmetrical icing takes place. The side of the ship exposed to the wind ices to a greater extent; this can lead to a listing of the ship toward the side having received the greater amount of ice.

Studies have shown that at wind speed up to 20-25m/sec on ships of the MFT type, the depositing of ice occurs mainly on the forward half of the vessel, including the frontal and lateral walls on the superstructure and bridgewings [6, 10]. In case of very rapid icing this could lead to the trim of the ship by the

bow, and even the emergence of the propeller from the water; this is particularly dangerous during icing when the ship is losing speed and maneuverability.

Section 3. Statistical Analysis Of Observational Materials

In the Northern Hemisphere, the icing of ships is common in fall, winter and spring (Table 1) and continues for about 3 months in the northern part of the Atlantic Ocean and 4 months in the Far Eastern seas. In the arctic seas, the icing of ships is possible even during the summer months at negative air temperature and heavy seas.

Table 1

Starting and Ending Dates of Ships' Icing and Their Frequency

Seas and Ocean Sectors	No of Cases	Period of Icing	Frequency %
NW part of Atlantic	85	15-Dec - 15 Mar	92
Norwegian & Greenland Seas	109	15 Dec - 31 Mar	77
Northern part of Atlantic	63	15 Dec - 15 Apr	92
Barents Sea	390	1 Jan - 15 Mar	78
Baltic Sea	21	15 Dec - 29 Feb	(85)
Baffin Sea, Hudson Bay	7	1 Dec - 31 Mar	(96)
Newfoundland region	15	1 Jan - 15 Mar	(79)
Bering Sea	185	1 Dec - 31 Mar	70
Sea of Okhotsk	337	1 Dec - 31 Mar	70
Sea of Japan	226	1 Dec - 29 Feb	85
NW part of Pacific	183	15 Dec - 31 Mar	79
Arctic seas (Kara, Laptevykh, East Siberian and Chukchi)	71	15 June - 15 Nov	100

A statistical analysis of more than 3,000 cases of the icing of fishing vessels indicates that the main reason for icing is spray from ocean water (89% of all cases). From the combined effects of spray and fog, or rain, or drizzle, icing rarely occurs (6.4% of the cases), while icing from the simultaneous effect of water spray and solid precipitation (snow) does not exceed [? - number not legible] .1% of the cases. In this manner, the cases of icing attributable only to fog, rain or drizzle comprise 2.7%.

In the arctic seas, the main reason for icing is also ocean spray which forms during heavy swell (50%) or simultaneous falling of precipitation and ocean spray on a ship (41%). The icing of ships caused by the settling of fog droplets on the supercooled surfaces of masts and superstructures comprises a total of 3% of the cases. The precipitation falling during negative air temperatures freezes to the deck and other ship structures. At this time a slight icing of the vessel takes place. Such a form of icing in the Arctic comprises a total of 6% [8].

The icing of ships has been recorded at air temperatures ranging from 0 to 55 [? - letters barely legible] m/sec. The lower the air temperature and the higher the wind speed, the more likely that icing will take place.

In Tables 2 and 3 we have listed data showing the distribution of cases of icing (in %) for various seas depending on temperature of air and water, direction and velocity of wind and severity of swell.

Based on certain data, at air temperature below -18°, icing caused by spray usually does not occur since the spray, striking the ship, is converted into fine dry ice crystals which do not stick to the structures' cold surface. The data (Table 2) from statistical processing refute this opinion. On the other hand, at air temperature below -18°, there occurred severe icing which could lead to catastrophic consequences.

Based on available data the icing of ships occurs fairly rarely at water temperature of 6° and above (Table 2).

Table 2

Distribution Of Cases Of Icing (%) For Various Seas Depending On Temperature Of Air And Water

Море (1)	(2) Температура воздуха				(3) Число случаев	(4) Температура воды					(3) Число случаев
	0,0–-4,0°	-4,1–-10,0°	-10,1–-15,0°	-15,1–-20,0°		-2,0–-1,1°	-1,0–0,0°	0,1–3,0°	3,0–6,0°	> +6,0°	
(5) Берингово (5)	15	60	23	2	570	6	6	78	10	-	517
Охотское (6)	19	64	12	5	340	20	26	50	4	-	297
Японское и Татарский пролив (7)	13	54	27	6	201	15	14	52	15	4	192
Запад Тихого океана (8)	27	63	10		231	16	19	55	10		239
Баренцево, Норвежское (9)	11	72	16	1	663	2	3	45	49	1	573
Балтийское (10)	56	33	11	-	46	-	11	89	-	-	36
Район Лабрадора (11)	21	55	18	6	90	11	32	49	8	-	82
Черное, Азовское (12)	23	36	41	-	22	-	24	48	28	-	21

Key: 1. Sea 2. Air Temperature 3. No of Cases 4. Water Temperature
5. Bering Sea 6. Sea of Okhotsk 7. Sea of Japan and Tatarskiy Strait
8. Western part of Pacific Ocean 9. Barents Sea, Norwegian Sea
10. Baltic Sea 11. Labrador Region 12. Black Sea and Sea of Azov

Table 3

Distribution Of Icing Cases (%) For Various Seas Depending On Wind Direction And Intensity Of Swell

Море (1)	Направление и скорость ветра (м/сек) (2)									Волнение (м) (4)			Период обледенения судов (5)
	271–360°		00–90°		91–180°		181–270°		Число случаев (3)				
	10	.10	10	10	10	10	10	10		1–3	3	Число случаев (3)	
(6) Берингово	12	43	16	23	1	1	2	2	567	55	45	464	X–III
(7) Охотское	19	34	3	10	1	3	10	20	323	73	27	257	X–III
(8) Японское и Татарский пролив	23	55	5	9	-	-	1	7	199	82	18	151	XII–II
(9) Запад Тихого океана	15	52	1	8	1	2	6	15	232	71	29	185	XI–II
(10) Баренцево, Норвежское	2	9	7	14	19	20	9	20	638	78	22	525	XII–III
(11) Балтийское		24		32	22	-	22	-	45	79	21	45	I–III
(12) Район Лабрадора	21	48	2	2	1	2	12	12	87	67	33	43	XII–II
(13) Черное, Азовское	55	-	-	45	-	-	-	-	11	-	-	-	I–III

Key: 1. Sea 2. Wind Direction and speed (m/sec) 3. Number of Cases 4. Swell (m) 5. Period of Ships' Icing 6. Bering Sea 7. Sea of Okhotsk 8. Sea of Japan and Tatarskiy Proliv 9. Western sector of Pacific Ocean 10. Barents Sea, Norwegian Sea 11. Baltic Sea 12. Labrador region 13. Black Sea, Sea of Azov.

The northern seas in the Atlantic are characterized by higher temperatures of water and air. In the south of the North Sea and Norwegian Sea, during the cold season the water temperature will fluctuate from 6 to 10°; therefore icing of ships does not take place.

In the northern sectors of these seas, harsher conditions are recorded. Here water temperature drops to 0.0-1.5° while during low air temperatures and stormy northeasterly winds, favorable conditions are created for a dangerous icing.

In the western and central parts of the Barents Sea, icing occurs at higher water temperatures reaching 5-6° and at this time icing is usually gradual. Only during stormy winds and a fall in air temperature below -10° can cases of rapid icing occur. In the eastern part of the Barents Sea and in the White Sea (which freeze over in winter), gradual icing can be recorded only from November-December.

Hydrometeorological conditions for icing in the western seas differ little from the conditions existing in the eastern seas. Cases of very rapid icing in the eastern seas are recorded at lower temperatures of air and water and at higher wind speeds.

Icing from fog, rain or drizzle is usual at air temperatures of -2, -5° and during slight winds; moreover, a very rapid icing from these causes does not take place.

From the total number of cases of icing in each sea, most common is the very rapid icing in the western seas (especially in the Norwegian Sea), i.e. 30%. In the eastern seas, it is recorded most often in the Sea of Japan, i.e. 17%.

In the northwestern sector of the Atlantic, Norwegian Sea, Greenland and Bering Seas, icing during winds blowing from the northern quadrant of the horizon occurs most frequently. For the northern sector of the Atlantic, the northwestern part of the Pacific, the Sea of Okhotsk and the Sea of Japan, icing is normally recorded during winds in the northwestern quadrant. Just for the Barents Sea, icing is most common during northeasterly winds.

According to statistical data, rapid icing sets in during a head wind or cross wind (88% of the cases). When the ship is moving downwind, the frequency of very severe icing is low, i.e. 12%. The main area of icing on the ship is the forecastle, deck, rigging and superstructure. Cases of icing over an entire ship are rare (2%).

On the ship structures, ice can build up with a thickness more than 20 cm; this takes place in approximately 50% of the icing cases. As a result of the spraying of ocean water and snow fall, ice with a thickness up to 100 cm freezes on deck.

The main means of struggling against ice include the scraping of ice (83% of the cases), passage to warmer regions (8%), decreasing the speed of the ship (4%), use of hot water (4%) and passage into ice (1%).

As studies have indicated, the rearward parts of low-pressured areas contain the most favorable conditions for the icing of marine vessels (Table 4); on an average, more than 50% of the cases of icing occur in such areas. Such a situation is particularly typical for the Sea of Okhotsk and the Sea of Japan, as well as for the western part of the Pacific. The second place in frequency is held by the cases of icing in the zones of warm fronts or the corresponding occlusion fronts. These cases are most typical for the regions of the Barents and Norwegian Seas.

If the ships enter the forward part of a powerful high-pressure system, icings are frequent even in the southern seas; the Caspian Sea, Sea of Azov and Black Sea and also in the Bering and Okhotsk Seas [2, 5].

Section 4. Hydrometeorological Complexes And Intensity of Icing

As we already indicated above, the main type of icing on marine vessels in frequency and risk for navigation and fishing industry is the icing from ocean spray and flooding by sea water during strong wind and low air temperatures. However, a strong wind and negative air temperature are still inadequate to begin the icing of a ship. Other conditions are necessary for spraying a ship with sea water.

Table 4

Synoptic Conditions For The Icing Of Ships From 1967-1969

(1) Море	(2) Тыл циклона (%)	(3) Передняя часть циклона (%)	(4) Прочие условия (%)	Число случаев (5)
Берингово (6)	57	32	11	442
Охотское (7)	70	23	7	312
Японское, Татарский (8) пролив	93	3	4	140
Западная часть Тихого океана (9)	75	19	6	182
Баренцево, Норвежское (10)	40	50	10	596
Балтийское (11)	4	66	30	44
Черное, Азовское (12)	79	16	5	18

Sea of Azov

Key: 1. Sea 2. Rear of Low-Pressure Area (%) 3. Forward Sector of Low-- (%) 4. Other Conditions (%) 5. No of Cases 6. Bering Sea 7. Sea of Okhotsk 8. Sea of Japan, Tatarskiy Proliv 9. Western Part of Pacific 10. Barents and Norwegian Seas 11. Baltic Sea 12. Black Sea and Sea of Azov.

In almost all the reports written by Soviet and foreign authors having investigated icing, special attention is directed to a determination of the hydrometeorological complexes during which the icing of ships takes place. Most of the authors consider the basic factors causing icing to be wind speed and air temperature. In a number of cases, they take into account the ship's heading and speed, temperature of surface water layer and sea action.

The various complexes (combinations) of hydrometeorological conditions influence the intensity of ship icing in different ways. During an identical combination of factors, there will ice over to a greater extent the ships which are smaller, with a lower freeboard, favoring a more frequent splashing of the ship by sea water.

For a determination of the rate (intensity) of ship icing based on the level of its danger, we tentatively differentiate three gradations of icing:

a) gradual icing;

b) rapid icing; and

c) very rapid icing.

These categories are different for the various vessel types. However, for the ships which are similar in size, displacement and design, the categories listed will be quite analogous; therefore, without great error, we can adopt the same criteria for intensity for the standard types of fishing ships where the length of 30-40m and displacement ranging from 300-500 tons.

In a determination of the icing intensity on fishing vessels of the MPT type and the one close to them in displacement (300-500 tons), for the basis we can take the ability of the crews on these ships to counteract the icing with the manual tools available (crowbars, picks, scrapers, etc) in order to provide security of the ship.

From this standpoint, for the indicated ships, we can adopt the following description for the intensity of icing, confirmed by the seminar on the "Ice" problem in September 1970.

1. Gradual Icing. The rate of ice accretion on a ship is not more than 1.5 t/hr. In this case, the crew on the MFT consisting of 25-26 men without outside assistance can handle the removal of ice from the ship.

2. Rapid Icing. The maximally possible intensity of icing is at the rate of 1.5-4 t/hr. At such an icing rate, it is difficult for the crew on the MFT to handle the removal of ice. In this case, the captain on the fishing ship is obliged to establish radio contact with the director of the expedition (flotilla) and with the shipowner, and to inform them at least once every 2 hours concerning the ship's position up to the stoppage of icing, or until the departure of the ship from the icing zone.

3. Very Rapid Icing. The rate of icing is more than 4 t/hr. At such an icing rate the ship's captain is required to maintain permanent contact with the officer in charge of the expedition (flotilla) and with the shipowner and to inform them continuously concerning the situation on the ship, adopt the most decisive steps involved in removing the ice from the ship and taking it from the dangerous zone, and, if necessary, to require assistance from rescue ships and other larger vessels.

The studies of hydrometeorological conditions conducted under full-scale conditions in the northern, western and Far Eastern seas from 1968-71 made it possible to establish the following hydrometeorological combinations which caused a varying intensity in the icing of fishing craft.

1. Gradual icing occurs during the spraying of a ship and (or) during the falling of supercooled precipitation, fog and smoking of the sea:

a) At any wind speed and air temperature ranging from -1 to -3°;

b) At wind speed ranging from 0 to 9 m/sec and air temperature below -3°,

2. Rapid icing occurs at wind speed ranging from 9-15 m/sec and air temperature from -3 to -8°.

3. Very rapid icing occurs:

a) at wind speed above 15m/sec and air temperature below -3^{o};

b) at wind speed ranging from 9-15m/sec and air temperature below -8^{o}.

In the northern part of the Atlantic Ocean and Barents Sea, which are exposed to the effect of the warm Gulf Stream, given the above-described hydrometeorological combinations, intensity of icing will be less if water temperature is above 2^{o}. Therefore in the regions indicated, it is necessary to take into account the water temperature during the establishment of the intensity of ships' icing.

Part 2. Synoptic Conditions And Recommendations On The Forecast Of Icing

Section 1. General Concepts

The hydrometeorological combinations causing a varying intensity in the icing of ships are caused by specific synoptic conditions.

In the northern and temperate latitudes in the Northern Hemisphore, as a rule the icing of ships takes place at intrusion of cold air masses in autumn, winter and spring into the commercial fishing areas and the regions of intensive navigation. This usually takes place in the rear of low-pressure areas during northern, northwesterly and westerly winds; it occurs less often in the forward part of a High during northeasterly and easterly winds.

The statistical data presented in Table 4 provide a graphic concept concerning the features involved in the development of synoptic processes favorable for the icing of marine vessels [5]. It is obvious from the table that in the rear part of a Low, we find an average of 60% of the cases of ship icing. In most cases, these are fairly well-developed deep Highs with pressure at center of 990 mb and below. Such a situation is especially typical for the Sea of Okhotsk and the Sea of Japan, as well as for the western part of the Pacific Ocean.

The advection of cold into the back edge of a high-pressure area during relatively strong winds is one of the typical conditions establishing the icing of ships. The icing zone at the rear of a High does not start immediately after the passage of the cold front but at a certain distance from it. This is explained by the fact that directly beyond the cold front, air temperature has not yet reached the low values necessary for icing. In addition, on passage of a cold front we note a change in the wind direction and speed, which leads in turn to a certain weakening of the wave action (swell).

Investigations have shown that in the Norwegian and Barents Seas, in 75% of the cases, the icing of fishing ships took place during cyclonic circulation; this indicates the tremendous role of cyclonic eddies in the formation of conditions favorable for icing. However, in the Norwegian and Barents Seas, icing of ships was recorded most often in the forward part of a high-pressure area.

Cases of icing within the zones of warm fronts or of the corresponding occlusion fronts hold second place in frequency of occurrence. These cases are most typical for the region of the Barents and Norwegian Seas; moreover, a particularly important role is played here by the pre-frontal intensification of wind. Depending on the direction in which the High will move, the fronts could be oriented in a latitudinal or meridional direction. In the first case, icing takes place during northeasterly winds, i.e. those blowing from the central regions of the Arctic; in the second instance, icing occurs during southerly or southwesterly winds blowing from the Eurasian continent.

In the Baltic Sea, the greatest threat of icing is brought by winds of easterly directions, blowing from the mainland, in the forward part of a High, or on the southeastern periphery of a low-pressure area.

Somewhat unique conditions causing icing developed in the Far East, where, along with the passage of deep highs, the icing of ships in the Sea of Japan and Okhotsk Sea is often favored by the winter monsoon circulation. In the regions of the Sea of Japan and Okhotsk Sea (less often in the Bering Sea region), the intrusion of cold air masses occurs along the eastern periphery of an intensive Asiatic Low; as a result, in these regions we often record the icing of ships during northwesterly and westerly winds; in a number of cases, they are noted during clear or slightly cloudy weather.

Favorable conditions for the icing of ships are created after the passage of deep Highs through the fishing areas of the Sea of Japan and the Okhotsk Sea.

On entry into the regions of the Sea of Japan, Okhotsk and Bering Seas, of deep Lows with pressure at center of 960–970 mb and below, in the rear parts of such Lows, in a number of cases a sharp decrease in air temperature occurs to −18 − −21° and a freshening of the northern and northwesterly winds to 10–12 points on the force scale occur, such as took place on 19 January 1965 in the Bering Sea and from 19–21 February 1966 in the Sea of Okhotsk, and at the southeastern coast of Kamchatka. Under such synoptic conditions, the very rapid icing of ships usually takes place (Figs. 1 and 2).

In the northeastern part of the Black Sea, in the vicinity of Kerch'–Tuapse and, especially in the region of Novorossiysk, as a rule the icing of ships is associated with the entry of cold air masses from the north via the Markhotskiy Pereval on the Main Caucasian Range (bora).

At the present time the prediction of the icing of ships, just as other dangerous and very dangerous hydrometeorological phenomenon, can be compiled based on a thorough analysis of the synoptic processes revealed from the data in charts for the weather at ground and aloft, particularly based on the AT_{850} Maps. As a result of analyzing the weather charts, the climatic data, information and icing of marine ships having occurred, and based on ship observations, the engineer-synoptician in the operating branch of the hydrometeorological service supporting the merchant marine and the fishing industry will gain a clear concept of the evolution of the baric field, the position of fronts, wind regime and air temperature; this will permit him to have the necessary data for developing a forecast on the basin, which is being supported, for periods ranging from 6 to 36 hours.

In compiling a forecast of the icing of ships, it is first necessary to develop a prediction of wind direction and speed, and of air temperature, since the prognosis of these elements is a point of departure in the compilation of a forecast for the ships' icing. At the same time, it is necessary to have in mind that during an offshore wind, the icing of ships in the 1–3 mile zone at the shore as a rule will be lacking, since in this zone the conditions necessary for the spraying of a ship are absent. In spite of the strong wind and low air temperature, the icing of ships in fields of pancake and broken ice will not be recorded.

During a prediction of the icing of ships, it is also necessary to utilize data concerning sea swell and temperature of the surface water layer, since the data can serve as additional material permitting us to consider the local features of some given region in a basin.

An analysis shows that the most favorable conditions for the icing of vessels develop in the vicinity of a cold trough at the 850 surface, the axis of which runs beyond the line of the cold front. Thence it follows that in the cases of the passage of deep occluded Lows when the cold center aloft coincides with the central axis of axis of the Low or its trough at the surface of earth (or water), at favorable values for wind speed and air temperature, we can anticipate the icing of ships near the Low's center.

The most typical cases of the extremely rapid icing of ships during winter are customary in the Far Eastern seas as a result of active synoptic processes which often trigger major contrasts in temperature. Here we can differentiate the following features in the development of synoptic processes:

1. If a Low situated in the vicinity of the northern islands of Japan begins to deepen rapidly and pressure at its center comprises 990mb and below, after its passage of 40°N, within 24-36 hours after the onset of the abrupt pressure drop, the threat of a very rapid icing of ships in the southern part of the Sea of Okhotsk is created.

2. If the Low attains 45-50°N, continuing to intensify, there appears the risk of a very rapid icing of ships in the vicinity of the Kuril Islands and in the basin contiguous to the southern coast of Kamchatka.

3. If the further advance of the Low occurs toward the northeast along the eastern coast of Kamchatka, after its passage of 55°N the threat originates of the icing of ships along the eastern shore of Kamchatka.

4. If the Low emerges into the central part of the Sea of Okhotsk, favorable conditions are developed for the icing of ships in the south of the Sea of Okhotsk and Tatarskiy Proliv and in the northern part of the Sea of Japan.

The leading part of the intensive High can also be favorable for creating conditions leading to the icing of ships. If the High is situated above the eastern region of the European USSR territory, while above the southern regions, there is situated a region of lowered pressure, a zone develops involving intensive northeasterly and easterly winds, and compassing the northern parts of the Caspian and Black Seas, as well as the Sea of Azov; this creates conditions for the icing of ships in these regions.

Section 2. Basic Forecasting Conclusions And Recommendations

1. The short-range prediction of marine craft should be compiled on the basis of a thorough analysis of hydrometeorological data arriving at the operational agency, and analysis of the development of synoptic processes, there is the utilization of ground-based and high-altitude weather charts.

2. The threat of the origin of the icing of ships in most instances exist in the rear part of a Low and-to a lesser extent-in the forward part. In both instances, we should record the active advection of cold air at heights of 1.5-3.0 km during strong wind and negative air temperatures.

3. For the development of conditions involving the spraying of a ship, a strong wind is required, blowing for a relatively extended time (3-6 hours and more) in one direction. The fields of pancake and broken ice obstruct the development of conditions for the spattering of ships, notwithstanding a strong wind and low air temperature. During an offshore wind, icing of ships will not occur in the littoral zone with a width of 1-3 miles, depending on height of shore.

4. The basic factor determining the threat of the icing of ships is the advection of cold air in the rear part of a Low, accompanied by a strong, in a number of cases stormy and even hurricane wind in the northern half of the horizon. Icing occurs relatively less often in the Lows during easterly, southeasterly and southerly winds.

5. The zone of icing at the rear of a Low usually does not begin immediately, but at a certain distance from the cold front.

6. A zone of very rapid icing of ships develops in the vicinity of the cold trough at the level of the 850mb surface.

7. In the far eastern seas, very rapid icing is customary after the passage of deep lows. Icing often occurs during clear or slightly cloudy weather as a result of the winter monsoon activity, creating the intrusion of cold air masses along the eastern periphery of the Siberian High.

8. One of the conditions favorable for the icing of ships is air temperature at AT_{850}, reaching -18° and continuing to drop.

9. A very rapid icing of ships occurs at wind speed exceeding 20m/sec and air temperature of -18° and lower.

10. During the prediction of the intensity of icing for the northern part of the Atlantic Ocean and the Barents Sea, which are exposed to the effect of the warm Gulf Stream, it is necessary to take into account the temperature of surface water layer if it is more than 2°.

Section 3. Examples of Ships' Icing

Example 1. From 5 to 10 January 1968, reports were received concerning the icing of 56 ships located at the western shores of Kamchatka and the Kuril Islands. Icing took place at air temperatures in the near-water layer of -10, -12° and northwesterly winds with a speed ranging from 15-20 m/sec. At this time, snowfalls were recorded.

Icing was recorded at the rear of deep Lows having shifted from the northern shores of Japan along the Kuril Islands into the Bering Sea. For the characteristics of the synoptic situations in the period under study, we cite the case for 5 January 1968 (Fig. 3).

At the rear of the Low moving from the lower reaches of the Amur River, there occurred the circulation of cold air (at the 850mb level, temperature was -34°). Passing above the sea the air became transformed and its temperature above Urup Island at the level of the 850mb isobaric surface comprised -20° (in the water surface layer, around -10°).

In order to seek out objective criteria for the possible icing of ships, we utilized the data collected at the Sobolevo Meteorological Station concerning the variation in H_{850} and temperature at this level (Fig. 4). It was considered that this station is most typical within the given region. The curve shown reveals that icing occurs both during a significant decrease in the 850mb geopotential and during its increase. The absolute temperature values are significant. Moreover, the cases of icing, especially rapid, are associated with low air temperatures at the 850mb level (-18, -30°). After 11 January when air temperature at the indicated level was above -11°, there was no icing.

Example 2. Icing in the forward part of a low on 5 February 1969 (Fig. 5). A deep low with pressure at center of 950mb was located above the northern regions of Japan. Judging by the baric tendencies and wind direction in the warm sector, the low had shifted northward. Air temperature at AT_{850}, entrained in the circulation of the low comprised -27° above Vladivostok. The intensive northern and northwestern winds, the wide zone of steady precipitation, low air temperatures (-10, -15°) and water temperatures (around 0°) created conditions leading to rapid icing. The research ship MFT "Akademik Ber" during this period experienced a very rapid icing in the northern part of the Sea of Japan. The accumulation of ice on the ship reached 5.2 t/hr.

Example 3. The example given (16 Feb 1969) shows that icing in the Baltic Sea (Fig. 6) develops during such synoptic situation when in a forward part of a Low or trough, extensive baric gradients are created, causing the propagation of cold air from the continent toward the sea.

Section 4. Scope Of Forecasts For Ships' Icing

1. The predictions of ship icing by the synoptic method are compiled for periods ranging from 6 to 36 hours depending on the periods for which the short-range weather forecasts are compiled for ships in the fisheries industry and merchant marine. These forecasts comprise an integral part of the weather forecasts for the corresponding regions in the World Ocean.

2. The prediction of icing is written for the ships with a displacement of 300-500 tons, with an indication of the anticipated intensity of icing.

3. The prediction of icing is also given with consideration of the features involved in the navigation of ships and their location, specifically:

a) a ship is moving at full speed into the wind at angles of 15-45°;

b) the ship is located in the open sea;

c) the ship is located near shore or near ice fields, and so on.

4. The prediction of the icing of ships is based on forecasting the wind and air temperature fields [See Note] [Note: The features involved in predicting a wind field at earth's surface (or at water surface) and air temperature have been set forth in the "Handbook On Short-Range Weather Forecasts," Part II (Chapters 1 and 2), Leningrad, Gidrometeoizdat, 1965].

Section 5. Warnings Of The Threat Of Ships' Icing

1. The warnings about the threat of ship icing are prepared by the operating agencies of the Hydrometeorological Service, supporting the merchant marine and the fisheries industry; this is done similarly to the warnings concerning other dangerous and very dangerous phenomena.

2. Gradual icing should be considered a dangerous occurrence, while rapid and very rapid icing should be considered as particularly dangerous.

3. In the warning notice concerning the danger of the icing of ships, there should be indicated:

a) number of warning;

b) time of inception of icing;

c) region of expected icing;

d) intensity;

e) expected direction and speed of wind; and

f) air temperature.

Example:

Warning Number 25.

Today, 17 December 1971 from 1500–1700 hours in the Sea of Okhotsk at the southwestern coast of Kamchatka in the region from Cape Lopatok Ust'-Bol'sheretsk, we expect extremely rapid icing of ships. The wind is northwesterly at 20–25 m/sec with air temperature of -10–15°.

Section 6. Numerical Forecast

Simultaneously with the synoptic techniques, we are developing another approach to the prediction, based on the hydrodynamic precalculation systems.

We can consider as established that from hydrometeorological conditions, the extent of the most dangerous spray-type icing is influenced by negative air temperatures, wind and, to a lesser extent, water temperature.

At the present time, there are very few hydrodynamic models with the aid of which a prediction is given of the pressure field at the surface. The actual models based on which we simultaneously precalculate the air temperature at surface are practically lacking.

For an experimental prediction, we considered a low-parametric model of an atmosphere, equivalent from a force standpoint to a real atmosphere. As the precomputed elements, we assume the pressure and air temperature at surface, and the geopotential of the average energy level, unambiguously associated with temperature at the average energy level. The problem is solved using the method of nets in time steps equaling 3 hours on a "Ural-2" computer. The timeliness of the forecast is 1 day in advance.

The computer prints out the air temperature, wind speed and the corresponding hydrometeorological combination. The data of the experimental forecast are properly oriented to the possible conditions of the ships' icing.

In discussing the practical realization of a hydrodynamic model on a computer, we should point out the difficulties involved with the shortage of raw data (particularly aerological) above the marine basins. Obviously to a considerable degree these difficulties can be surmounted with the aid of satellite data [9].

More precise hydrodynamic models will probably be developed for a numerical forecast of icing on ships. After testing the setup under operational conditions, we can form a judgment concerning its effectiveness. Only the initial steps have been made along these lines. However the development of the numerical models technique is opening a broad prospect for the numerical predictions of the icing conditions. In the presence of forecasting values for temperature and wind speed at surface, as a result of numerical or a statistical forecast, we can estimate the intensity of icing based on the methods explained below.

Part 3. Mathematical Techniques Of Estimating The Intensity Of Ship Icing

Many a theoretical studies conducted so far (1,6,7,9) have made it possible to obtain important practical results dividing the opportunity:

a) to describe qualitatively the physics involved in the icing process;

b) to pinpoint the possible methods of a quantitative estimation of the icing intensity on individual ship structures and on the entire ship, according to prescribed hydrometeorological parameters;

c) to point out possible ways for solving the problem of a numerical prediction of the icing conditions and ships and

d) to substantiate on a physical basis the hydrometeorological combinations leading to icing.

For the forecaster and the mariner, it is important to know what total amount of ice will accumulate within a certain time on a ship or its individual structures during given hydrometeorological conditions, at prescribed parameters of incoming water or spray cloud. We discuss below certain methods for estimating the intensity of icing on ships; these techniques can be recommended for these purposes.

Section 1. Theoretical Models Of Ships' Icing

The theoretical studies indicate that the intensity of icing (rate of ice accretion in t/hr) on a ship depends on an entire range of hydrometeorological conditions and design features of a ship.

One of the techniques of estimating the intensity of icing is based on the heat balance of the surface which is becoming iced over [1, 6]. The intensity of ice accretion on a surface of 1 cm^2 arranged perpendicular to the spray flow is computed based on the equation:

$$J = \alpha \frac{T_a - T_z + 2.6 \frac{L_{исп}}{p}(E_{T_a} - E_{T_z})}{L_{кр} + C_л(T_z - T_0) + C_w(T_0 - T_z)} . \qquad (1)$$

where:

α= heat transfer coefficient depending on wind speed and configuration of icing surface (Fig. 7);

$L_{[?]}$, $L_{исп}$ = heat of crystallization and evaporation of ice (Appendixes 2 and 3);

$C_л$, C_w = specific heat capacities of ice and water (Appendixes 4 and 5);

T_a= air temperatures;

T_z = temperature of water particles in a fresh-water or spray cloud (Appendix 1);

E_{T_a}, $E_{T_Л}$ = vapor pressure of water at air temperature of the water surface (Appendix 6) and at air temperature of icing .face (Appendix 7);

ρ = atmospheric pressure;

$T_Л$ = temperature of forming ice during established icing process;

2.6 = coefficient having the dimensions of g= deg/cal.

The equation is suitable for calculating both the spray-type and the fresh-water ice accretion. In the first case, it is necessary to compute the T_z value as a function of the size of drop, time of its flight and temperature of ambient air (Appendix 1). Apparently in the second case the supercooled drops will acquire the temperature of the ambient air. A verification of the equation against data from full-scale observations indicated a good qualitative agreement of the theory with the experiment [9].

Based on the experimental data indicated above, it is feasible to accomplish a theoretical estimation of the intensity of ice accretion as a function of temperature of air and water, wind speed and geometry of the icing surface at various combinations of T_n and T_a in the entire stochastic range of variations in these parameters.

We have given below a description of the models for which we conducted calculations, plus an analysis of the results obtained [1].

Model 1; fresh-water icing. This type of ice accretion occurs in a supercooled fog, rain and during the smoking of the sea. In the estuaries of large rivers during a strong wind, we also record the fresh-water icing of ships.

In the model, it is assumed that $T_a = T_\eta$ and the supercooling of water particles is 1^o as compared with T_a. In the field of T_a, V_H, the icing rate varies within the limits from 0.01 -0.15g/hr per sq cm of plane surface. For the round surfaces (antenna, stays, halyards with a diameter of 1cm), these values will increase by approximately 3 times at a slight wind speed and by twice when the winds have a speed ranging from 30-40m/sec, which is determined by the dependence of α on the shape of icing surface and on wind speed.

In nature, the temperature of a water particle can be below T_a by 5^o and more. Then the icing rate increases by approximately 3 times and even more. Consequently the fresh-water icing will be all the more intensive, the greater the difference $T_a - T_\chi$.

Model 2; Spray-Type Icing In Seas With Low Salinity (15 parts per thousand), such as the Baltic, Caspian, and Sea of Azov. The supercooling of water sprays in relation to T_a was assumed to equal 2^o, while $T_a = T_\eta$. The quantity of ice forming in this case is 4-5 times greater than in model 1, and varies in the limits of 0.05-0.4g/hr per sq cm of plane surface.

Model 3; Spray-Type Icing In Water With High Salinity (34 parts per thousand), such as the Far Eastern, Northern and Western. We have considered several cases.

1. The temperature of surface water layer is close to freezing temperature (-1.7^o). The difference in $T_a - T_\eta$ is $1-2^o$ (1^o up to -16^o and 2^o below -16^o). In Fig. 8a, we have presented such a case. It is obvious from the figure that function $\mathcal{J}$ has maximal values at T_a = minus $12-14^o$ and gradually decreases toward $T_a = -4^o$, on the one hand, and toward $T_a = -22^o$, on the other hand. Under the condition that T_a = minus $24-26^o$, the formation of ice becomes more gradual; this is explained by the precipitation of salts in this range and by the increase in C_η. Then the intensity of icing once again will increase slightly.

We have shown in Fig. 8b a similar case calculated for a cylindrical surface with a diameter of 1cm. It is obvious from the figure that on a unit of such a surface, approximately twice as much ice accretes as on a flat surface.

2. The temperature of surface layer is the same, i.e. -1.7°. The difference $T_a - T_n$ comprises 3-4° (3° up to -16° and 4° below -16°). The appropriate results from the calculations have been listed in Fig. 8c. As is evident from the figure, function $\mathcal{J}$ has a maximum at temperature of -16°; moreover, in this case the values for the quantity of ice are lower than in Fig. 8a. Just as in case 1, here function $\mathcal{J}$ also has minimal values at air temperatures of -24°, -26° and at temperatures close to that of the freezing of water (-1.85°).

It is apparent from comparing Figs. 8c and 8a that, with a variation in the temperature of ice, the icing intensity changes significantly.

3. The effect of surface temperature on the icing conditions have been examined in the following example: water temperature at sea surface was assumed to equal + 2° (Fig. 8d). The water which has fallen onto a ship as a result of spattering became cooled according to an exponential law. Just as in the previous cases, the flight time of the water particles was assumed to equal 1 sec; the difference $T_a - T_n$ = 1-2° (1° to -16° and 2° below -16°). It is evident from Fig. 8d that, with a rise in water temperature, there is a decrease in the total amount of ice occuring on 1 sq cm of flat surface by 0.5 - 1.2g/hr.

Based on the experimental data we estimated the proportions between T_a and T_n, which were at the basis for the construction of the icing models which have been reviewed.

The models indicated can be utilized for estimating the intensity of ship icing. As a verification shows, the theoretical results are close to the observational values. The calculation technique has been presented in more detail in Section 2.

A somewhat different approach to a study of the theory of icing on ships is being developed by L.G. Kachurin, L.I. Gashin and I.A. Smirnov [7], and also L.A. Klyuchnikova [9].

The first authors solved the problem of the icing of a cylinder of infinite length placed in a flow of supercooled aerosol and found a correlative relationship between the theoretical criterion obtained for a cylinder and the intensity involved in the icing of an actual ship. Their calculation technique presented in Section 3 is based on this.

L.A. Klyuchnikova has solved the problem of icing on deck. In an investigation of the processes of icing on a deck, a consideration of heat transfer between the deck and water, between water and air in the area which becomes flooded with water is significant. A determination of the intensity of icing in this case reduces to:

a) a calculation of temperature distribution in the deck under the effect of heat exchange between the deck and air prior to the arrival of water on deck;

b) a calculation of temperature distribution in the water at the instant of its reaching the crystallization temperature as a result of heat exchange of water with air and the deck; and

c) a calculation of the rate of ice formation in water under the influence of its further cooling on the deck.

All three problems are solved by means of integrating the heat conductivity equations for a nonstationary regime of the third kind.

A theoretical analysis of icing on a ship deck permits us to make certain qualitative conclusions concerning the counteracting of its icing. According to L.A. Klyuchnikova's data, the design of the deck and of the side ports should provide a certain lag in the water hitting the deck, in order to utilize its heat reserve for disrupting the ice rind which has already formed. After this it is necessary to drain the water through the side ports which should be periodically opened and, with the aid of artificial heating, should be maintained in an unfrozen condition. A convex deck with instantaneous draining of water overboard will ice over according to the same laws as does the superstructure.

Section 2. Example Of Calculating The Total Quantity Of Ice Forming During The Icing Of A Vessel

Based on Eq. (1), we will compute the total amount of ice on the MFT Akademik Ber.

The horizontal area which became iced over on the A ademik Ber equaled 139.0 sq m (area of upper deck from superstructure toward the bow section -128.3 sq m; and passageways on upper deck -10.7 sq m). The lateral plane surface of the ship is 45.7 sq m: lifeboat area is 3.66 sq m, bulwark area to superstructure (half) = 20 sq m, area of entry lock = 2 sq m, area of superstructure and deckhouse (half) = 20.0 sq m. The cylindrical surfaces had an area equaling roughly 3.2 sq m (loading boom = 0.6? sq m, bow mast = 2.57 sq m). The surface of the bow mast became ic -coated only for 5-8m from the deck. We are assuming the total surface of the mast in order to take into account the weight of ice which will form on the rigging.

Based on data for 0100 hours on 12 January 1969, air temperature (T_a) = -10.8^o; water temperature (T_w) was $+0.8^o$; wind velocity (V) = 15m/sec; vessel speed V = 9 knots; the relative wind bearing (K) = 29^o; and atmospheric pressure was 1025mb. At 0200 hours $T_a = -11.2^o$, $T_w = +0.6^o$, V = 11m/sec, V = 9 knots and K = 39^o. The freezing of water began at 0045 hours. Consequently the raw data for computing the amount of ice which accreted on the ship in 1 hour 15 minutes will be for a horizontal surface:

α = 5.1 cal/sq cm • hr • degrees (Fig.7); based on V = 15m/sec and V_c = 9 knots = 4.6m/sec, the speed of apparent wind = 19.6m/sec; $T_л = -7.8^o$ (based on data from research [6], ice temperature is 3^o higher than air temperature;

$T_{(?)} = -2.2^o$ (from Appendix 1 based on the given temperature of surface layer, $T_w = +0.8^o$ and the transit time of sprays equaling 2 sec); $L_{исп}$ = 667 (from Appendix 3, based on [? - word not legible] and salinity of ice equaling 30 parts per thousand); $L_{зам}$ = 4.0 (from Appendix 2, based on freezing temperature of water with a salinity of $34^o/oo$);

$C_? = 2.4$ (from Appendix 4, based on $T_л = -7.8^o$ and its salinity of $30^o/oo$); $C_w = 0.95$ (from Appendix 5, based on T and its salinty of $34^o/oo$); and $E_{T_a} = 5.5$ (from Appendix 6); $E_{T_л} = 3.1$ (based on Appendix 7).

Having substituted the original values into Eq. (1), we derive:

$$J = 5{,}1\frac{-7{,}8 + 2{,}2 + 2{,}6\frac{667}{1025}(5{,}3 - 3{,}1)}{4{,}0 + 2{,}4(-10{,}8 + 7{,}8) + 0{,}95(-7{,}8 + 2{,}2)} = 1{,}14 \quad \text{g/hr} \cdot \text{sq cm}$$

By 0200 hours, i.e. in 1 hour 15 minutes, the ice had accumulated the following quantity:

$$1.14 + 1.14 \cdot 0.25 = 1.4 \text{g/hr} \cdot \text{sq cm}$$

The ship had followed a heading of 281° to Askol'd Island; thereupon at 0250 hours, it changed to a heading of 337°. In 50 minutes (from 0200 hours to 0250 hours, on the flat surfaces, the following amount of ice had accreted

$$J = 4.2\frac{-8{,}2 + 2{,}5 + 2{,}6\frac{667}{1025}(5{,}08 - 3{,}08)}{4{,}0 + 2{,}4(-11{,}2 + 8{,}2) + 0{,}95(-8{,}2 + 2{,}5)} = \quad 1.2 \text{ g/hr} \cdot \text{sq cm}$$

where:

$\alpha = 4.2$ (based on $V = 11\text{m/sec}$ and $V_c = 9$ knots, Fig. 7)

$T_a = -11.2°$; $T_w = 0.6°$; $T_л = -8.2°$ (higher than [? - value missing in source] by 3°); $T_з = -2.5°$ (from Appendix 1); $L_{исп} = 667$ (from Appendix 3); $L_{зам} = 4.0$ (from Appendix 2); $C_л = 2.4$ (from Appendix 4); $C_w = 0.95$ (from Appendix 5); $E_{T_a} = 5.08$, and $E_{T_л} = 3.08$.

In 50 minutes the amount of ice which has formed was 1.2 g/hr $\cdot$ 0.83 = 1.0 g.

As a total during the time from 0045 hours to 0250 hours, the maximal amount of ice having precipitated on 1 sq cm of the flat ship surfaces constituted:

1.4 + 1.0 = 2.4 g.

This is tantamount to an ice thickness of 2.7cm if we assume the density of ice to equal 0.9 g/ccm.

On the horizontal surface (of a medium fishing trawler) equaling 139.0 sq m during the time from 0045 hours to 0250 hours, the amount of ice comprised:

$$139.0 \text{ sq m} \cdot 2.4\text{g} = 3.3 \text{ tons.}$$

The wind's angle on the bow was in the limits from 29-39°. Hence on the side surface of the ship a quantity of ice equaling:

$$45.7 \text{ sq m} \cdot 1.4\text{g} \cdot \cos 29^\circ + 45.7 \text{ sq m} \cdot 1.0\text{g} \cdot \cos' 39^\circ = 0.9\text{t}$$

was deposited.

As a total on the horizontal surfaces from 0045 hours to 0250 hours, there had accumulated:

$$3.3 + 0.9 = 4.2 \text{ tons of ice.}$$

For the cylindrical surfaces, the coefficient of heat emission equals: $\alpha = 2.6$cal/sq cm • hr • degrees (Fig. 7); based on $V = 15$m/sec and $V_c = 9$ knots (from 0045 minutes to 0200 minutes) $\alpha = 2.5$cal/sq cm • hr • degrees (Fig. 7); based on $V = 11$m/sec and $V_c = 9$ knots (from 0200 hours to 0250 hours).

On one square centimeter of cylindrical surface, from 0045 hours to 0200 hours, the following amount of ice had accreted:

$$J = 2,6 \frac{-7,8 + 2,2 + 2,5 \frac{600}{1025}(5,8 - 3,1)}{4,0 + 2,4(-10,8 + 7,8) + 0,95(-7,8 + 2,2)} +$$

+0.6 • 0.25 = 0.75g/sq cm, while on the entire surface 3.2 sq m = 0.02 ton.

Analogously for the period from 0200 hours to 0250 hours, on the cylindrical surfaces, the following amount of ice had accumulated:

$$0.6 \text{ g} \cdot 3.2 \text{ sq m} = 0.02 \text{ ton.}$$

In this way by 0250 hours, on the cylindrical surfaces the following amount of ice had accreted:

$$0.02 + 0.02 = 0.04 \text{ t.}$$

As a total for the ship, the amount of ice reached

$$3.3 + 0.9 + 0.04 = 4.24 \text{ t.}$$

From 0250 hours to 0645 hours, the vessel had followed a heading of 337°. Air temperature was -10.7°, -11.2°; water temperature was 0.3, + 0.5°; wind speed was 9-10 m/sec; speed of ship was 8-9 knots; and the angle of wind on the bow was 39°. Consequently based on Eq. (1), the rate of ice formation was around 1.0 g/hr ($T_{a} = -11.0°$, $T_{\Lambda} = -8.0°$, $T_{\chi} = -2.5°$, $T_{w} = 0.4°$ and α = 4.2 for a horizontal surface; α = 2.6 for a round surface, E_{T_a} = 5.08, $E_{T_{\Lambda}}$ = 3.1, $L_{зам}$ = 4.0, $L_{исп}$ = 667, C_{Λ} = 2.4, and C_{w} = 0.95).

For the time from 0250 hours to 0645 hours, on the horizontal surfaces of the medium fishing trawler the following amount of ice had accumulated:

$$139.0 \text{ sq m} \cdot 1.0 \text{ g} \cdot 3 \text{ hours } 55 \text{ minutes} = 5.4 \text{ tons;}$$

on the lateral surfaces

$$45.7 \text{ sq m} \cdot 1.0 \text{ g} \cdot 3 \text{ hours } 55 \text{ minutes} \cdot \cos 39° = 1.4 \text{ t;}$$

while on the cylindrical surfaces;

$$3.2 \text{ sq m} \cdot 0.6 \text{ g} \cdot 3 \text{ hours } 55 \text{ minutes} = 0.07 \text{ t.}$$

At 0645 hours the spattering of water had stopped. In this way during the icing period, the following amount of ice had formed on the ship:

$4.24 + 5.4 + 0.07 = 11.1$ t; this is close to the observed value of 13.7 t.

At ice density of 0.9 g/ccm, its thickness on a horizontal flat surface will comprise on an average:

$$(2.4 + 3.9):0.9 = 7.0 \text{ cm.}$$

and the amount on the lateral surface will be

$(1.4 \cdot \cos 29^{o} + 1.0 \cdot \cos 39^{o} + 1.0 \cdot 3.9 \text{ hrs} \cdot \cos 39^{o}): 0.9 =$ 5.6 cm.

As observations have shown, the ice thickness on deck reached 1.2-8.0 cm; on the superstructure it was 3.5-8.0 cm, while on the mast and boom, the ice thickness ranged from 5.0-8.0 cm.

Section 3. Mathematical Method (State Hydrologic Observatory, Leningrad Meteorological Institute) for Estimating the Intensity of Ship Icing

The total amount of ice forming on a ship is determined by the rate of ice formation and the size of the area exposed to spattering (spray), which in turn depends on the type of vessel, its heading relative to the wind and direction of wave propagation.

At the basis of the given mathematical technique for predicting the intensity of icing, we have placed the correlative relationship between the complex theoretical criterion which combines the hydrometeorological parameters determining the ice formation rate, and the actual rate of the icing of vessels of the MFT type and of the fishing seiner type. Such a relationship has been depicted in Fig. 9.

As a common criterion of the most dangerous icing of ships (caused by ocean spray) in the open sea, we utilize the calculated icing rate of a horizontal cylinder existing under the same hydrometeorological conditions as a ship at sea.

The theoretical basis for the criterion of icing rate on a ship is the theory involving the icing of an infinite cylinder in a flow of supercooled aerosol, developed in the reports [6, 8].

For the construction of a correlative graph, we have resorted to data concerning the icing of MFT type of ships having completed special cruises in the northern and eastern seas from 1967-1971, plus data concerning the icing of fishing smacks, containing quantitative characteristics of a process's intensity. In addition we have utilized data concerning the icing on Japanese research vessels [14]. Other conditions being equal, the

icing intensity depends on the ship's heading relative to the wind: it is maximal during small angles on the bow. For the construction of a correlative graph, we employed data concerning the icing of ships only in case of headings relative to the wind of 0-40° to port and starboard. In this way the technique utilized permits us to compute the maximal intensity of the process, expected under the given hydrometeorological conditions.

The correlation between criterion N and intensity of ship icing $d\,P/d\tau$ calculated for the entire combination of points proved to equal $K = 0.93 \pm 0.04$.

In an evaluation of the statistical reliability of the correlation, we should keep in mind that for practical purposes, a high accuracy of the estimation of intensity is not necessary; it is adequate to divide the entire possible range of icing rate into several subranges. Therefore the equation of regression can be depicted by a straight line. The calculation reduces to the equation of regression:

$$d_p/d\tau = (-0.4 + 0.8\ N)\ \text{t/hr.}$$

where $[N] =$ cm/hr.

The confidence interval proved to be relatively narrow. Thus for the confidence coefficient 0.95 N = 5.cm/hr, the confidence limits run with deviation of $\pm$ 0.11 N from the regression equation.

For the practical utilization of the technique suggested, we have developed a calculation system consisting of the following.

For certain reference values of salinity and water temperature, we have established the value of criterion N as a function of the wind speed and air temperature.

In Fig. 10 we have portrayed a working graph for salinity $S = 35^{\circ}/oo$ and water temperature $\theta_\beta = +1^{\circ}$. The deviation from actual salinity determining $L_1 T_\phi$ and actual water temperature from the reference values is considered by way of introducing corrections.

The value of the criterion for actual conditions can be represented as:

$$N = \tilde{N}\left[1 + \ln\frac{L_{AS}}{L_s} + \frac{\Delta T_\phi}{T_\phi - \theta_a} + 0.04(\tilde{\theta}_b - \theta_b)\right], \qquad (2)$$

where:

L_s =crystallization heat of ocean water with salinity [? - value lacking in source]; $T\phi$ = temperature of crystallization front; and [? - symbol not legible]$\Delta T\phi$ = deviation of temperature in crystallization front at salinity S from temperature of crystallization front in case of salinity of $35^o/oo$.

The relationship curve for the correction $A = \ln L_{\Delta S}/L_s + \Delta T\phi/(T\phi - \theta_a)$ on salinity has been shown in Fig. 11; Figure 12 shows the relationship curve for the correction $B = 0.04\ (\tilde{\theta}_b - \theta_b)$ plotted against water temperature.

The calculation of maximal intensity of a ship's icing (expressed in tons/hr) is accomplished based on data concerning air temperature - θ_b ; wind velocity = V m/sec; water temperature = θ_b', and its salinity S^o/oo.

1. Based on wind speed and air temperature, utilizing the curve (Fig. 10), we find the reference value for the criterion N (with accuracy up to tenths).

2. Based on the value of salinity and air temperature, with the aid of the graph (Fig. 11), we find the value of correction A (with accuracy up to 100ths).

3. Based on water temperature, with the aid of the graph (Fig. 12), we find the value for the correction B (with accuracy up to 100ths).

4. The criterion is computed based on the formula with an accuracy up to tenths;

$$N = \tilde{N}(1 + A + B). \qquad (3)$$

5. From the working curve (Fig. 13) in respect to value N, we extract the intensity (rate) of icing (tons/hr with accuracy up to tenths)

Example 1. Let us estimate the icing rate of the medium fishing trawler Stepan Andreyev in the Baltic Sea in March 1969, under the following hydrometeorological conditions;

$$\theta_a = -4.0^\circ;\ V = 14\ m/sec;\ \theta_b = +0.7^\circ;\ S = 15^\circ/oo.$$

The value N = 1.7 cm/hr corresponds to the initial values $\theta_a = -4.0^\circ$ and V = 14 m/sec in the graph (Fig. 10). The value for the correction A corresponding to a salinity of $15^\circ/oo$ and air temperature of -4° equals -0.58 according to the graph (Fig. 11). The correction B for water temperature plus 0.7° taken from the curve (Fig. 12) equals +0.02.

Substituting the values of corrections A, B and the N - value into Eq. (2), we derive

$$N = 1.7(1 - 0.58 + 0.02) = 0.8\ cm/hr.$$

The icing rate of a ship extracted from the graph (Fig. 9) corresponding to the corrected value of criterion N comprises 0.4 tons/hr. Under the given hydrometeorological conditions, the actual rate is 0.5 tons/hr.

Example 2. Let us compute the icing rate, utilizing the observational data for a ship of a medium fishing trawler class Akademik Ber on 3 February 1969.

The icing conditions were as follows:

$$\theta_a = -12.7^\circ;\ V = 10.3\ m/sec;\ \theta_b = -0.2^\circ;\ \text{and}\ S = 34^\circ/oo.$$

Based on V = 10.3 m/sec and $\theta_a = -12.7^\circ$, with the aid of the graph (Fig. 10), we find the value N, which in the given instance proved to equal 4.2 cm/hr. The correction A for S = $34^\circ/oo$ and $\theta_a = -12.7^\circ$ will equal -0.02 according to the graph (Fig. 11). The correction B for θ_b equals -0.2° taken from the graph (Fig. 12) equals + 0.04. Substituting the A, B and N - values into Eq.(2), we obtain N equals 4.3 cm/hr. The icing rate of a vessel taken from the set of curves (Fig. 9) equals 3.1 t/hr. In reality the ship has become iced over at a rate of 3.4 t/hr.

Section 4. Simplified Method Of Calculating The Intensity Of Ship Icing

In a number of instances, the weather forecasters in the operating agencies, as well as the captains and navigating personnel, especially of fishing vessels, need to be able to determine approximately and rapidly the icing rate of a vessel or group of vessels.

The full-scale studies of the hydrometeorological conditions causing icing, conducted on ships in the fisheries industry in the Far Eastern and northern seas from 1968-1971 made it possible to disclose certain features in the icing rate of ships depending on hydrometeorological conditions, primarily on wind speed and on air temperature [9, 11].

For a practical estimation of the icing rate of ships of the medium fishing trawler and similar types (in regard to dimensions) it is sufficient to know the speed of the course (observed) wind (V_k) and air temperature (T_a)

Under the conditions causing the spattering of a ship by sea water and during negative air temperatures below -3^o, the intensity of ice buildup on a ship will increase with a freshening of the wind or with a drop in air temperature and particularly with simultaneous freshening of wind and drop in air temperature, if other conditions affecting the icing rate stay the same, i.e. the heading and cruising speed of ship, wind direction, frequency of spraying the ship by sea water, etc.

With the conditions indicated, the rate of ice accumulation on a ship will depend on the number n, which equals the product of the course (heading) wind speed V_k times the air temperature T_a (degrees), i.e. n equals $V_k \cdot T_a$. The higher the n-number, the greater the icing rate of a ship. The intensity of ship icing is normally expressed by the amount of ice in tons, which is deposited during icing of a ship in one hour. In Fig. 14 we have shown a graph reflecting the dependence of icing rate of ships in the medium fishing trawler class and those ships similar in size, on the n - number for a simplified calculation.

While measuring during cruising the air temperature and speed of course wind, for the mariners it is no great difficulty to obtain the n-number and, based on the graph (Fig.14), determine the icing rate of a ship $\mathcal{J}$ (t/hr). Thus at wind speed of 15 m/sec and air temperature of -7°, the n-number will equal 105. Based on the graph, to the number n = 105, there will correspond an icing rate of 1.4 t/hr.

The set of curves has been constructed from calculating the conditions maximally favorable for the icing of a ship, i.e. the ship is cruising at full speed at an angle of 15-45° to the wind direction. This graph can also be utilized for estimating the possible icing during the utilization of a weather forecast. In this case, the wind force which is being predicted, expressed in force points, should be converted to m/sec and multiplied times the predicted air temperature. We obtain the n-number, based on which it is easy to find the possible icing rate. In this case, it is advantageous to choose the average predicted air temperature.

Taking into account that the operating agencies of the Hydrometeorological Service predict the actual wind rather than the course wind, for the obtainment of a more precise value for the icing rate, to the average predicted wind speed after conversion to m/sec one should add the average travel speed of the ship also expressed in m/sec. For the derivation of the n-number, it is necessary to multiply the indicated value times the average value for the air temperature which we are predicting.

The operating agencies in the Hydrometeorological Service can obtain raw data for a simplified method intended to calculate the icing rate of vessels from the hydrometeorological observations obtained from the ships.

Section 5. Determining The Weight Of Ice During The Icing Period

It is extremely important for the mariners, particularly the navigators of fishing vessels, to know the actual weight of ice received by a ship during the icing stage. This provides the opportunity of determining to what category of intensity we should relegate the incipient icing, and what its danger is for the ship. However a precise determination of the weight of ice

having accumulated on a ship presents an extremely complex problem. For this purpose, it is necessary to measure the thicknesses of ice at many points on the deck, rigging, sparring, mechanisms etc at various heights, including the masts, booms, guys and stays. These measurements can be performed only in a shelter when sea swell is lacking. In addition, it is necessary to know the ice density at various points on the ship. We can determine the weight of ice received by a ship by means of a heeling experiment before and after icing, and also by means of measuring the ship's draft.

The investigation of the indicated question under natural conditions on the medium fishing trawler type of ships afforded the possibility of establishing an approximate relationship between weight of ice received by a vessel during icing, and the average thickness of ice having accumulated on the ship. For this purpose it is adequate to perform three measurements each on the woodrail on the port and starboard side in the bow section at the windlass, in the central section at the bow mast and in the stern section opposite the sweeping winch. From six measurements, we can calculate the average thickness of ice on the woodrail (expressed in mm) and based on the set of curves (Fig. 15), we can establish the weight of ice on the ship (Q) in tons. If the measurements of ice thickness on the woodrail are performed hourly, we are able to determine the icing rate of a ship expressed in tons/hour, deducting the weight of ice which the ship had an hour previously.

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Appendix 1

Temperature of Water Drop As Function Of Air Temperature And Transit Time

(a) Время полета капли	(b) Температура воздуха 0°	-2°	-5°	-10°	-15°	-20°	-30°
	(c) Первоначальная температура воды -1°,7						
1	-1,42	-1,75	-2,24	-3,07	-3,89	-4,72	-6,37
2	-1,19	-1,79	-2,70	-4,21	-5,72	-6,23	-10,25
3	-0,99	-1,83	-3,08	-5,16	-7,25	-9,33	-13,50
4	-0,83	-1,86	-3,39	-5,96	-6,52	-11,09	-16,22
5	-0,69	-1,82	-3,66	-6,62	-9,79	-12,55	-17,48
10	-0,28	-1,95	-4,46	-6,63	-12,61	-16,36	-25,35
	(c) Первоначальная температура воды 0°						
1	0	-0,31	-0,78	-1,56	-2,34	-3,12	-4,68
2	0	-0,58	-1,44	-2,86	-4,32	-5,76	-8,64
3	0	-0,80	-2,00	-3,99	-5,98	-7,98	-11,97
4	0	-0,96	-2,46	-4,37	-7,39	-9,86	-14,79
5	0	-1,15	-2,86	-5,73	-6,59	-11,46	-17,19
10	0	-1,68	-4,08	-6,17	-12,25	-15,34	-24,51

Key: a. Transit time of drop b. Air temperature c. Initial water temperature -1.7°, etc.

	(c) Первоначальная температура воды +2°						
1	1,69	1,26	0,71	0,13	-0,65	-1,44	-2,09
2	1,42	0,85	-0,08	-1,46	-2,90	-4,34	-7,22
3	1,20	0,40	-0,79	-2,73	-4,76	-6,76	-10,77
4	1,01	-0,08	-1,43	-3,92	-6,28	-8,64	-12,76
5	0,85	-0,28	-2,11	-4,85	-7,74	-10,62	-16,34
10	0,27	-1,27	-3,72	-7,80	-11,80	-15,77	-24,12

Appendix 2

Effective Thawing Heat of Fresh-Water and Sea Ice

T_{λ} = ice temperature	Salinity (°/00) 0	5	10	15	20	25	30	35
-1°	80,12	59,08	37,98	16,87				
-2	80,62	69,60	58,53	47,45	36,36	25,28	14,19	3,11
-3	81,13	73,57	66,95	58,32	50,70	43,07	35,44	30,92
-5	82,14	77,39	72,58	67,77	62,96	58,14	58,32	48,51
-8	83,65	80,42	77,13	73,83	70,54	67,23	63,94	60,63
-10	84,66	81,92	79,12	76,31	73,51	70,70	67,89	65,08
-15	87,18	85,04	82,85	80,66	78,46	76,25	74,05	71,84
-20	89,70	87,96	86,21	84,42	82,64	80,85	79,06	77,28
-23	91,21	89,84	88,42	86,99	85,56	84,13	82,69	81,25
-25	92,22	91,21	90,13	89,06	87,98	86,90	85,81	84,72
-30	94,74	93,09	93,09	92,24	91,37	90,50	89.63	88,76

Key: a. T_{λ} = ice temperature

b. Salinity (°/oo)

Appendix 3

Evaporation Heat of Distilled Water, Fresh-Water- and Sea-Ice
(in cal/g)

T_l	Salinity (^{o}/oo)							
	0	5	10	15	20	25	30	35
-1^o	80.12	59.08	37.98	16.87				
-2	80.62	69.60	58.53	47.45	36.36	25.28	14.19	3.11
-3	81.13	73.57	66.95	58.32	50.70	43.07	35.44	30.92
-5	82.14	77.39	72.58	67.77	62.96	58.14	58.32	48.51
-8	83.66	80.42	77.13	73.83	70.54	67.23	63.94	60.63
-10	84.66	81.92	79.12	76.31	73.51	70.70	67.89	65.08
-15	87.18	85.04	82.85	80.66	78.46	76.25	74.05	71.84
-20	89.70	87.96	86.21	84.42	82.64	80.85	79.06	77.28
-23	91.21	89.84	88.42	86.99	85.56	84.13	82.69	81.25
-25	92.22	91.21	90.13	89.06	87.98	86.90	85.81	84.72
-30	94.74	93.94	93.09	92.24	91.37	90.50	89.63	88.76

Appendix 4

Effective Heat Capacity of Fresh-Water and Sea Ice at Various Temperatures and Salinities (expressed in cal/g · degr)

Ice temperature	Salinity (°/00) 0	5	10	15	20	25	30	35
-1°	0,502	20,373	40,245	60,115				
-2	0,501	5,646	10,792	15,938	21,084	26,229	31,374	36,519
-3	0,499	2,837	5,176	6,513	9,852	12,191	14,540	16,868
-5	0,495	1,337	2,178	3,021	3,862	4,704	5,546	6,388
-3	0,490	0.801	1,113	1,424	1,736	2,047	2,357	2,670
-10	0,486	0,679	0,871	1,064	1,257	1,450	1,642	1,835
-15	0,477	0,572	0,665	0,760	0,855	0,948	1,043	1,138
-20	0,468	0,538	0,609	0,679	0,750	0,820	0,890	0,960
-23	0,463	0,733	1,003	1,273	1,545	1,816	2,087	2,358
-25	0,459	0,551	0,643	0,735	0,826	0,919	1,010	1,101
-30	0,450	0,469	0,488	0,507	0,526	0,545	0,563	0,581

Key: a. ice temperature

b. Salinity (°/oo)

Heat Capacity C_p of Sea Water at Standard Atmospheric Pressure Depending on Temperature and Salinity (in cal/g·degr)

T°	Соленость (°/оо)								
	0	5	10	15	20	25	30	35	40
5°	1,003	0,995	0,987	0,980	0,972	0,965	0,959	0,952	0,945
2	1,005	0,997	0,988	0,980	0,973	0,965	0,958	0,952	0,945
1	1,006	0,997	0,989	0,981	0,973	0,965	0,958	0,952	0,945
-1	1,007	0,998	0,969	0,981	0,973	0,965	0,958	0,952	0,945
-2	-	-	-	-	0,973	0,965	0,958	0,951	0,945
	-	-	-	-	-	-	-	0,951	0,945

Key: a. Salinity (°/₀₀).

Appendix 6

Elasticity of Saturated Water Vapor Above Water (millibars)

T_s	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°
-30°	0,51	0,46	0,42	0,38	0,35	0,31	0,28	0,26	0,23	0,21
-20	1,25	1,15	1,05	0,96	0,88	0,81	0,74	0,67	0,61	0,56
-10	2,86	2,64	2,44	2,25	2,08	1,91	1,76	1,62	1,49	1,37
0	6,11	5,68	5,27	4,90	4,55	4,21	3,91	3,62	3,35	3,10

Appendix 7

Elasticity of Saturated Water Vapor Pressure Above Ice (millibars)

T_s	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°
0°	6,11	5,62	5,17	4,76	4,37	4,02	3,68	3,38	3,10	2,84
-10	2,60	2,38	2,17	1,98	1,81	1,65	1,51	1,37	1,25	1,14
-20	1,03	0,94	0,85	0,77	0,70	0,63	0,57	0,52	0,47	0,42
-30	0,38	0,34	0,31	0,28	0,25	0,22	0,20	0,18	0,16	0,14

Fig. 1. Weather Map at 1500 Hrs on 19 January 1965.

Fig. 2. Weather Map at 1500 Hrs on 20 February 1966

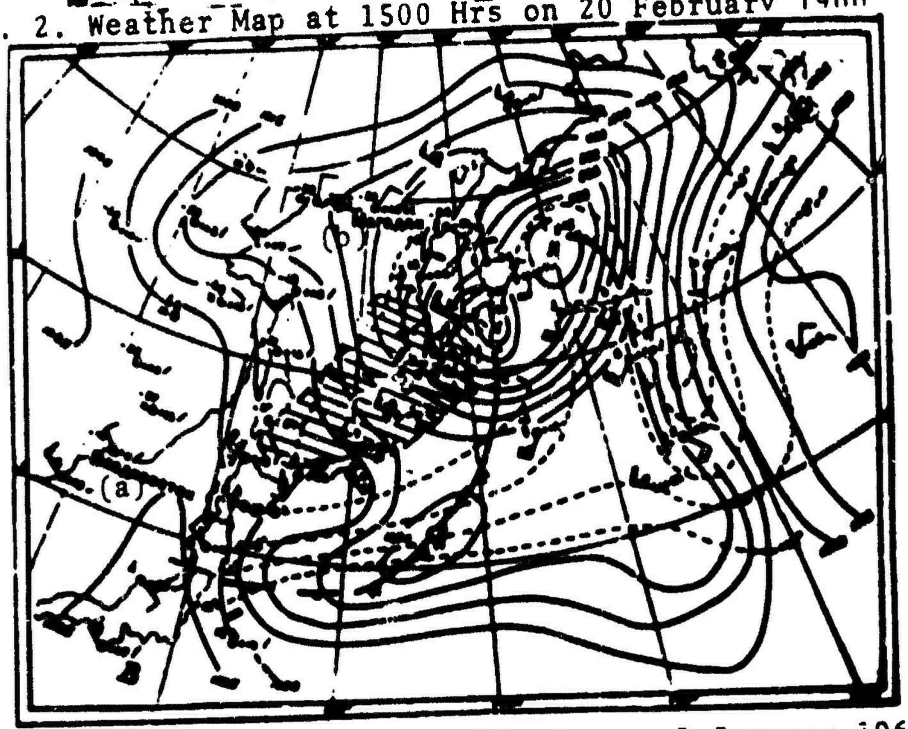


Fig. 3. Weather Map at 0000 Hrs on 5 January 1968.
Key: a. Vladivostok b. Magadan.

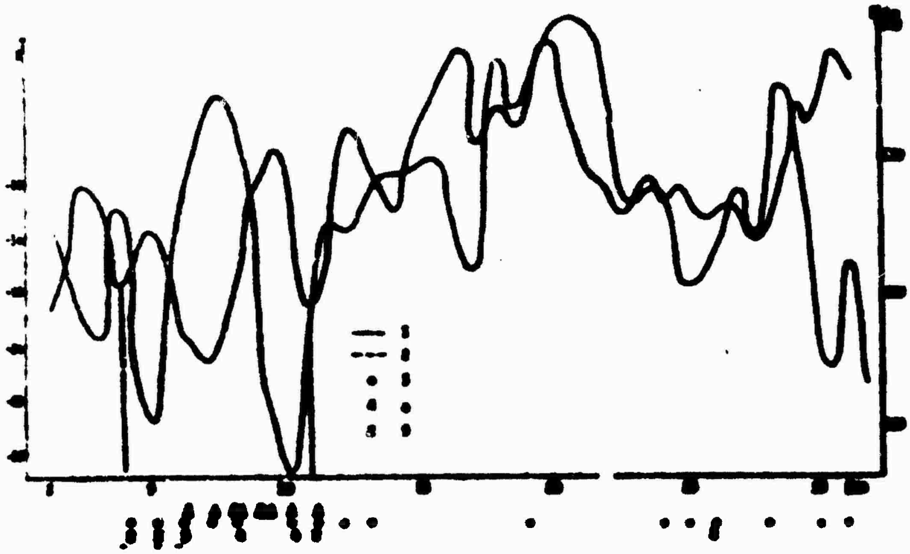


Fig. 4. Temperature Variation and Geopotential at AT_{850} Level;

Sobolevo Station in January 1968.

1 - air temperature; 2 - geopotential height;

3 - slight icing; 4 - rapid icing; and 5 - number of ships having become iced.

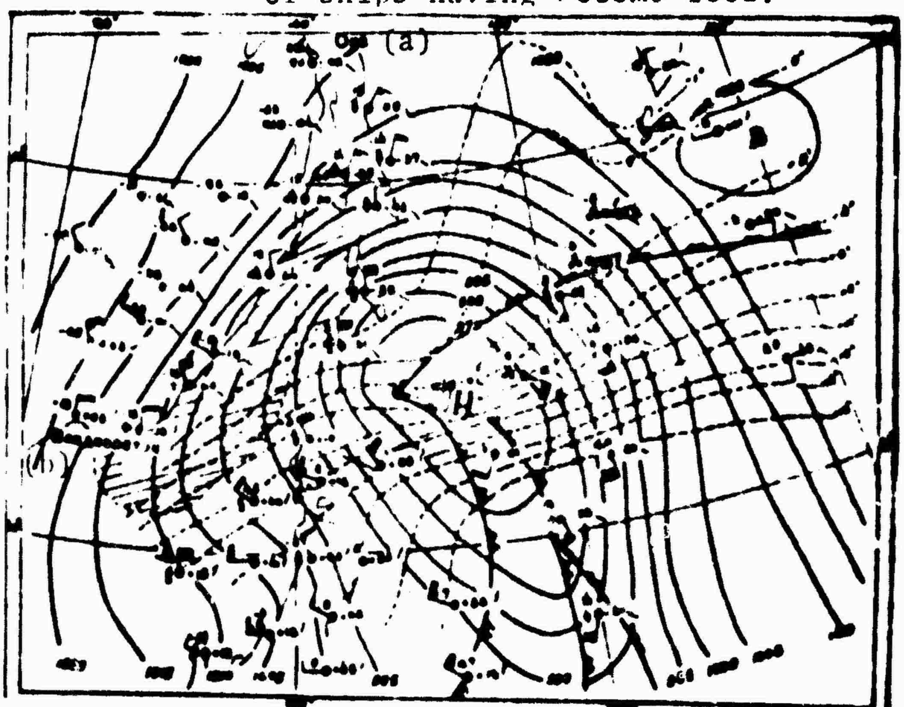


Fig. 5. Weather Map at 1200 Hrs on 5 February 1969.

Key: a. Oka b. Vladivostok

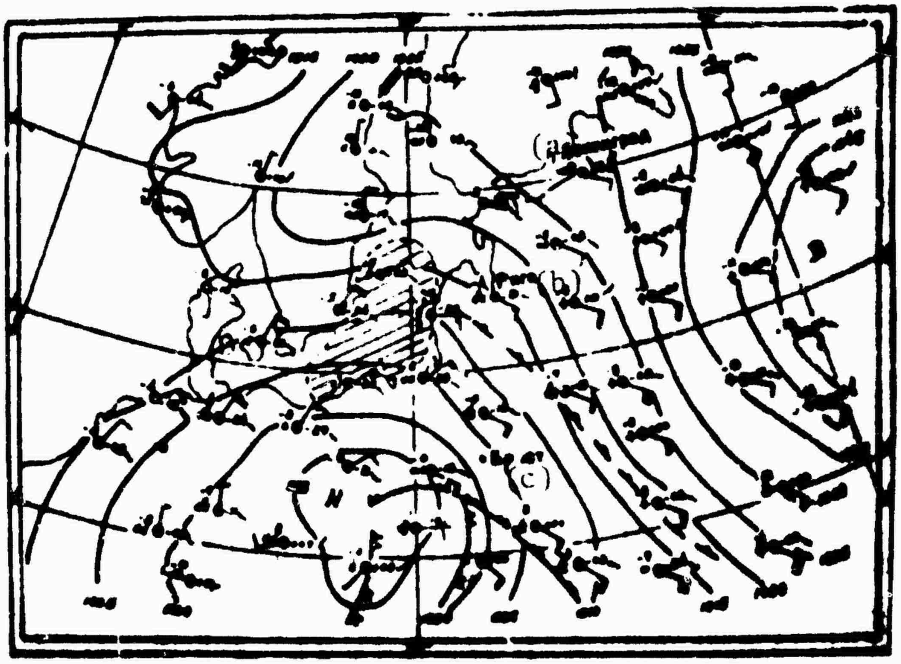


Fig. 6. Weather Map As of 0000 Hrs on 16 February 1969.
Key: a. Leningrad b. Riga c. Brest

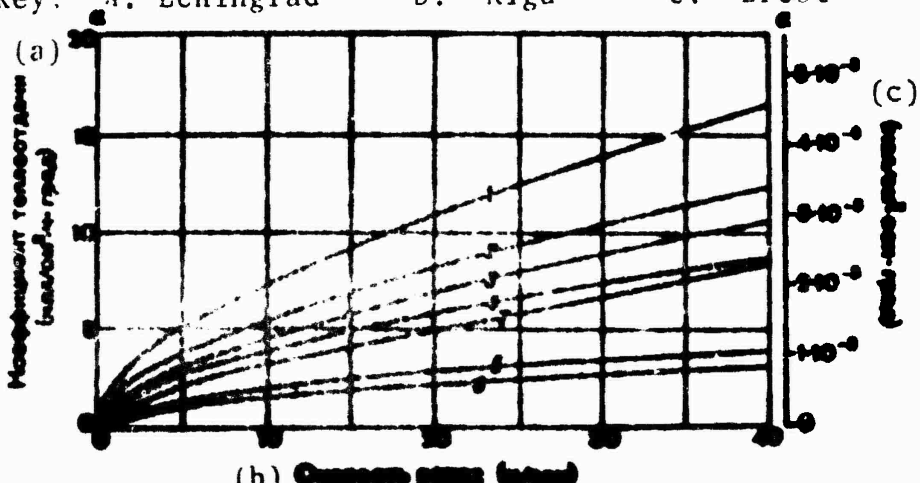


Fig. 7. Heat transfer Coefficient of Ship's Round Structures vs Speed of Apparent Wind. Diameters: 1 - 1 cm; 2 - 2 cm; 3 - 3 cm; 4 - 5 cm; 5 - 30 cm; 6 - 50 cm; and 7 - flat surface.

Key: a. Heat transfer coefficient (cal/sq cm·hr·degr)
b. Wind speed (m/sec)
c. (cal/sq cm·sec·degr).

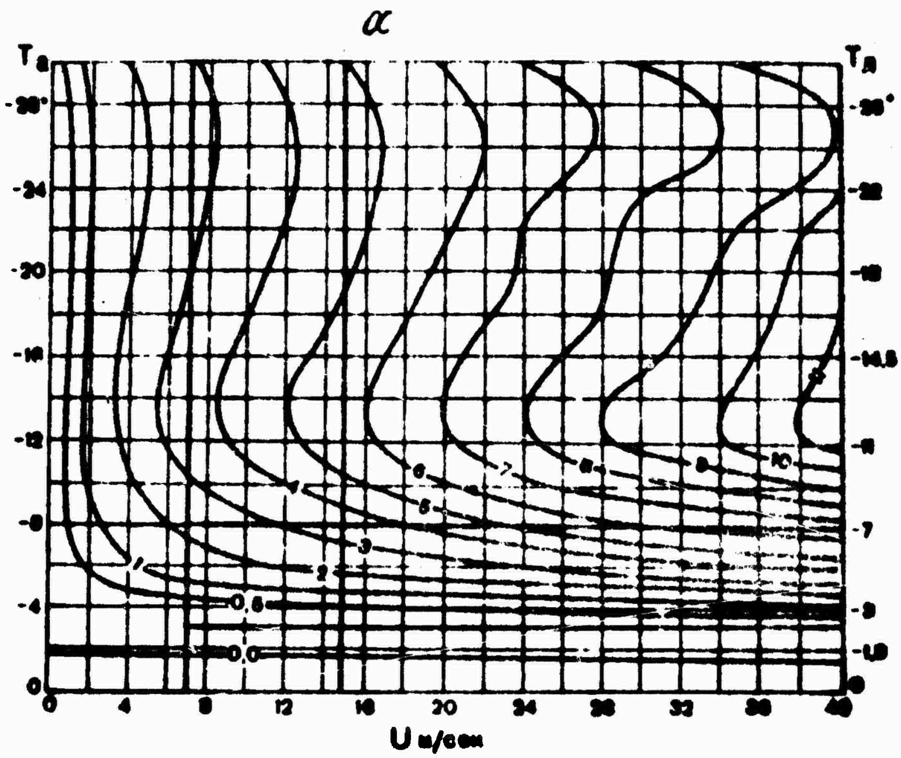


Fig. 8. Amount of Ice (g/hr) Which Can Form on 1 Sq Cm of Surface During Icing of a Ship.

a- flat surface, T_W= 1.7°; S = 34°/oo; $L_{зам}$*=4.0; $L_{исп}$**= 601-700; $C_л$ 0.6 - 36.5.

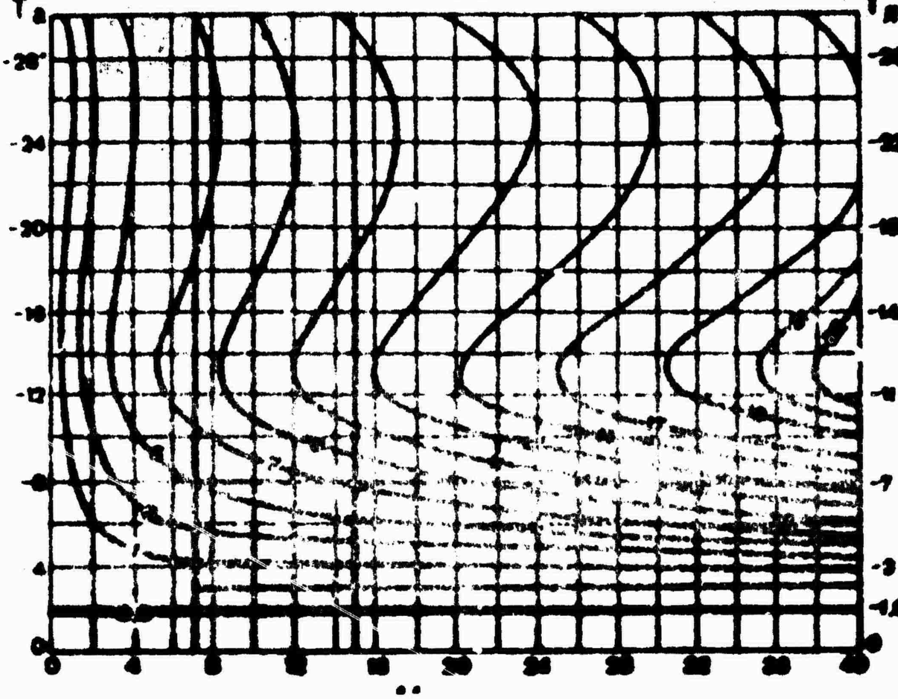
b- cylindrical surface, T_W =-1.7°, S = 34°/oo; $L_{зам}$ = 4.0; $L_{исп}$= 60 = 601+700; $C_л$ = 0.6+30.

c- flat surface, T_W = -1.7°; S = 34‰; $L_{зам}$ = 4.0; $L_{исп}$ = 601+700; $C_л$ = 1.0 + 36.5.

d- flat surface, T_W= 2°, S = 34°/oo; $L_{зам}$ = 4.0; $L_{исп}$ = 601+700; $C_л$ = 0.6 + 36.5.

* [Here and elsewhere, subscript "зам" = "freezing"]
** [" " " " "исп" = vaporization.]

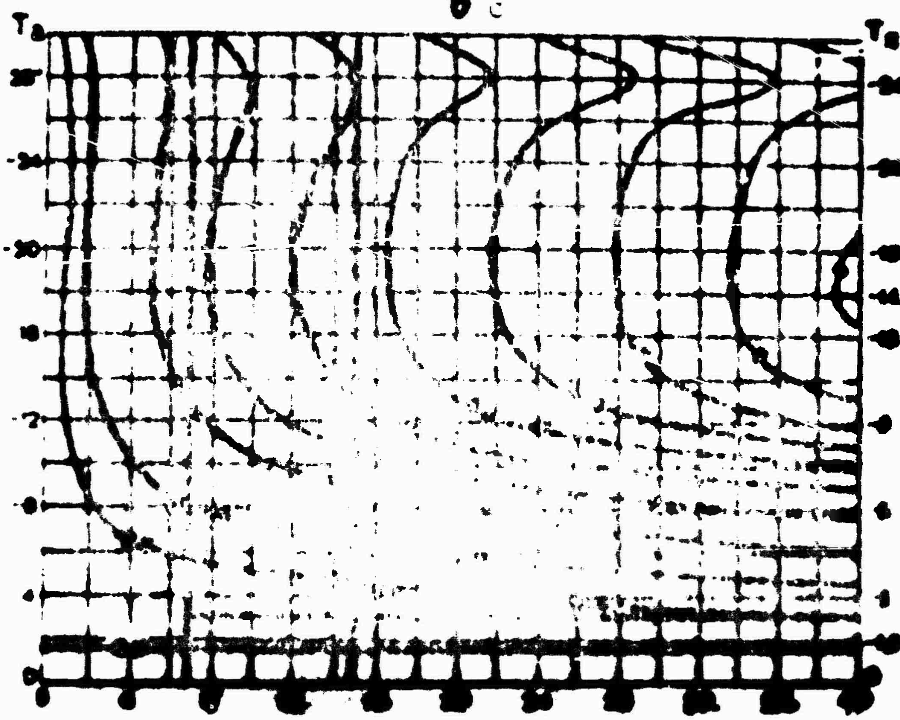
δ_b



U m/sec

c

δ c



U m/sec

Fig. 8 (cont'd).

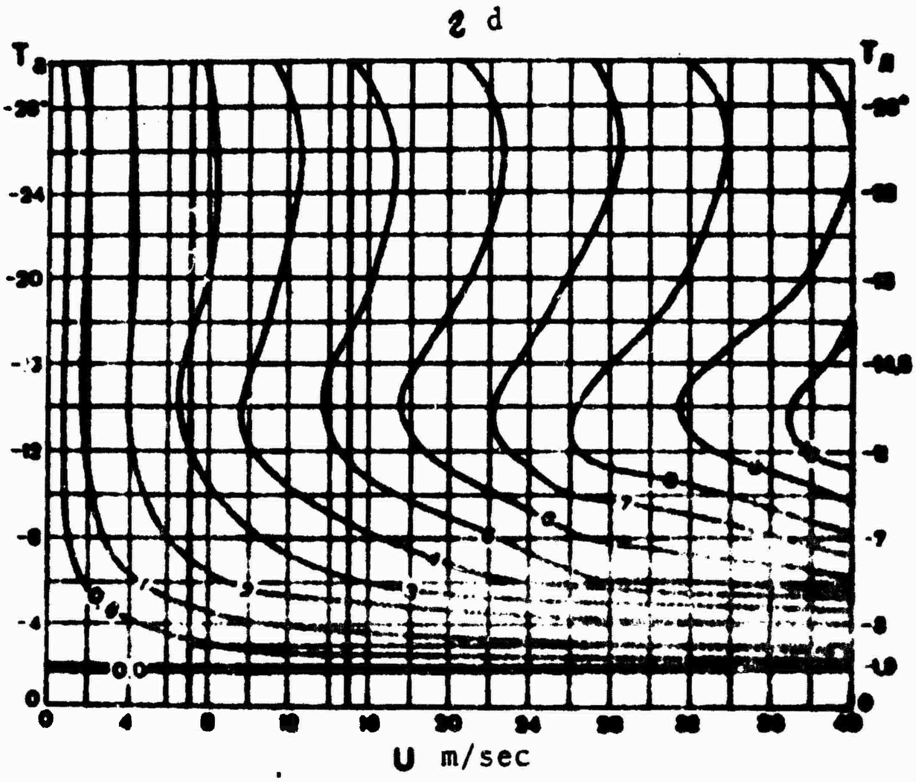


Fig. 8 (concluded).

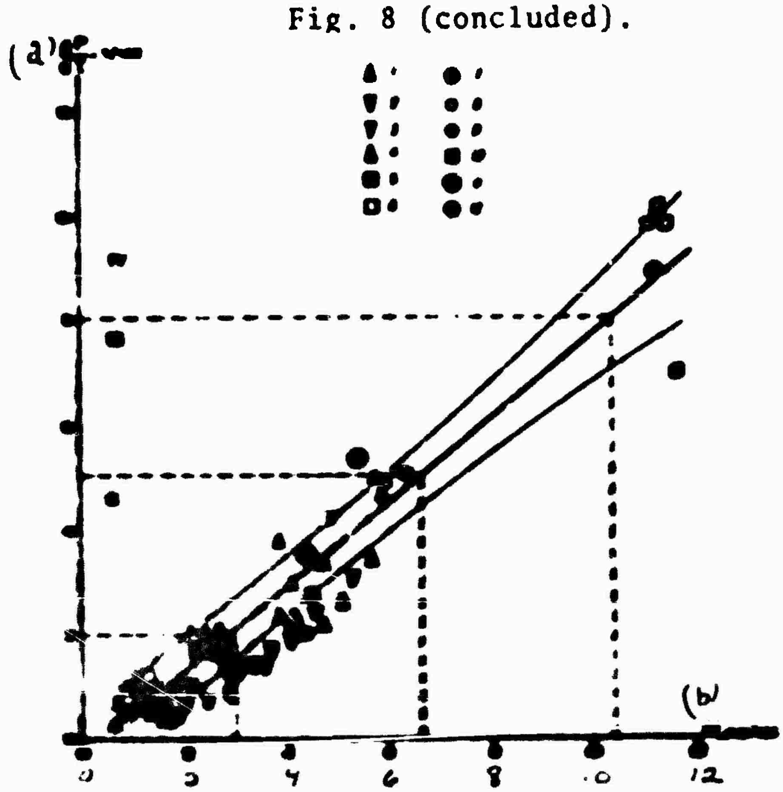


Fig. 9. Relationship Between Icing Rate (N cm/hr) and Actual Icing Rate of MFT Type of Vessel in Open Sea ($dP/d\tau$, t/hr).

[caption cont'd on next page]

[Fig. 9 caption cont'd];
1 - MFT Akademik Ber, January-February 1967-1969, Sea of Japan; 2 - MFT Professor Somov, 1969, Barents Sea; 3 - Japanese ships Obari, Totosa, 1961-1963, Sea of Japan; 4- MFTF (medium fishing trawler-freezer) Alaid, January 1968, Barents Sea; 5 - MFT Polyarnik, January 1968, Barents Sea; 6 - MFT Boksitogorsk, Sevsk, and Sebezh, January 1966, Bering Sea; 7 - seiner-876 Kurs, 1967, Barents Sea; 8 - MFTF-8480, January 1968, Sea of Japan; 9 - seiner-827, Ordzhonikidze, December 1967, Barents Sea; 10 - MFTF-8462, February 1969, Sea of Japan; 11 - MFTF-4211, MFT Stepan Andreyev, 1969, Baltic Sea; MFT Kedrovyy, February 1968, Berkng Sea; 12 - MFT Professor Somov, February 1971, Barents Sea.

Key: a. dP/dτ t/hr b. N, cm/hr.

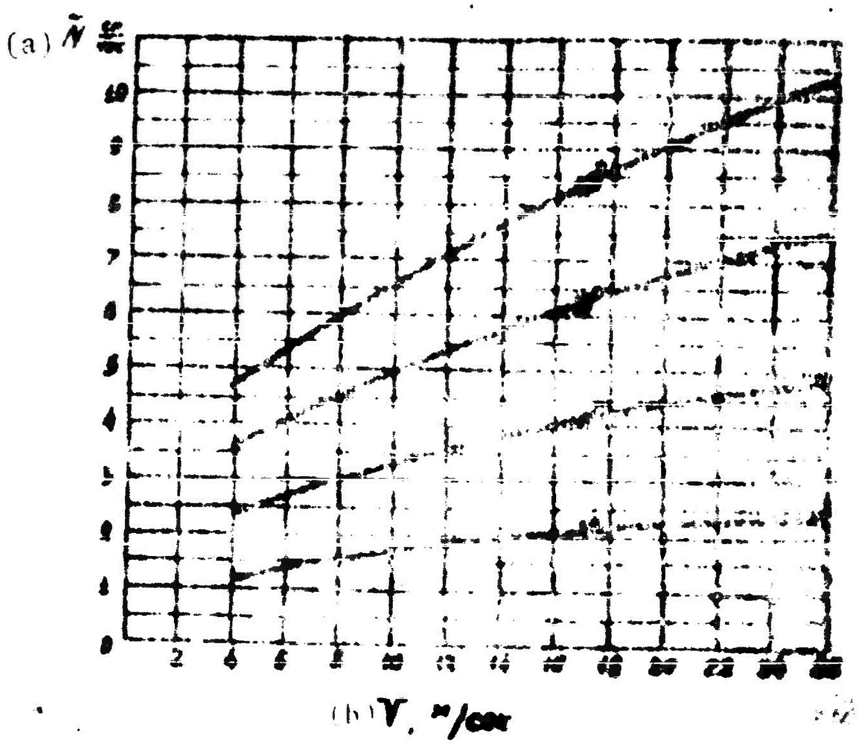


Fig. 10. Reference Criterion Value $\tilde{N}$ vs Air Temperature θ_a and Wind Speed V at Fixed Sea Water Temperature of +1° and Salinity of 35°/oo.

Key: a. N, cm/hr
b. V, m/sec.

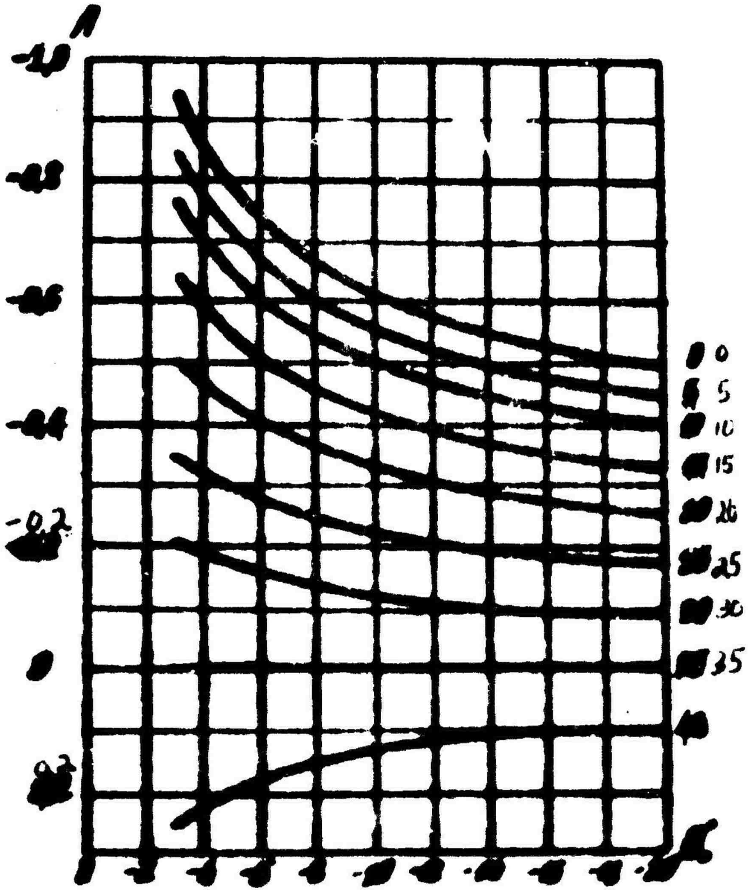


Fig. 11. Value of Correction A = $\ln L_{\Delta s}/L_s + \Delta T_\phi/T_\phi - \theta_a$

vs Salinity and Air Temperature.

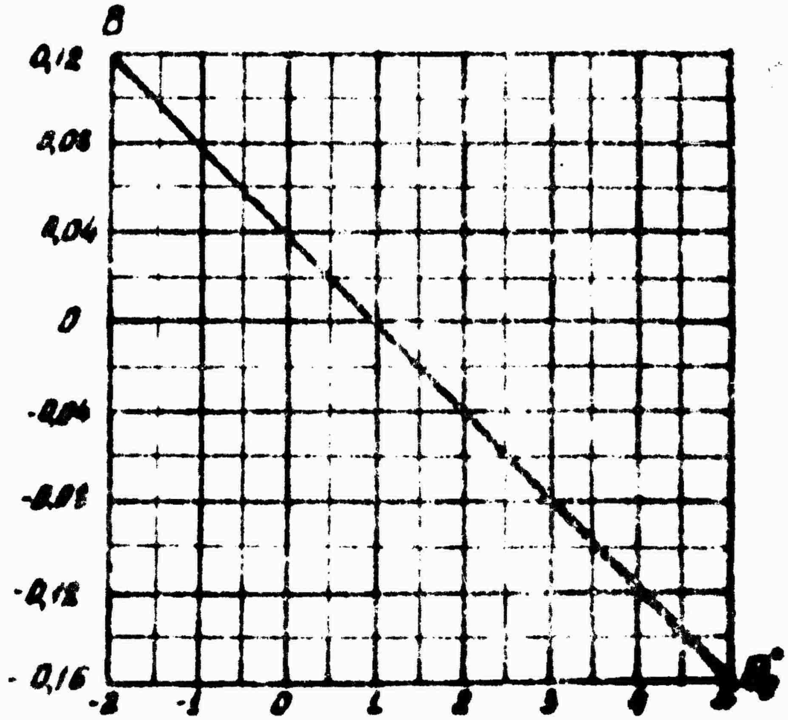


Fig. 12. Correction Value $B = 0.04 \cdot (\tilde{\theta}_B - \theta_B)$ vs Water Temperature.

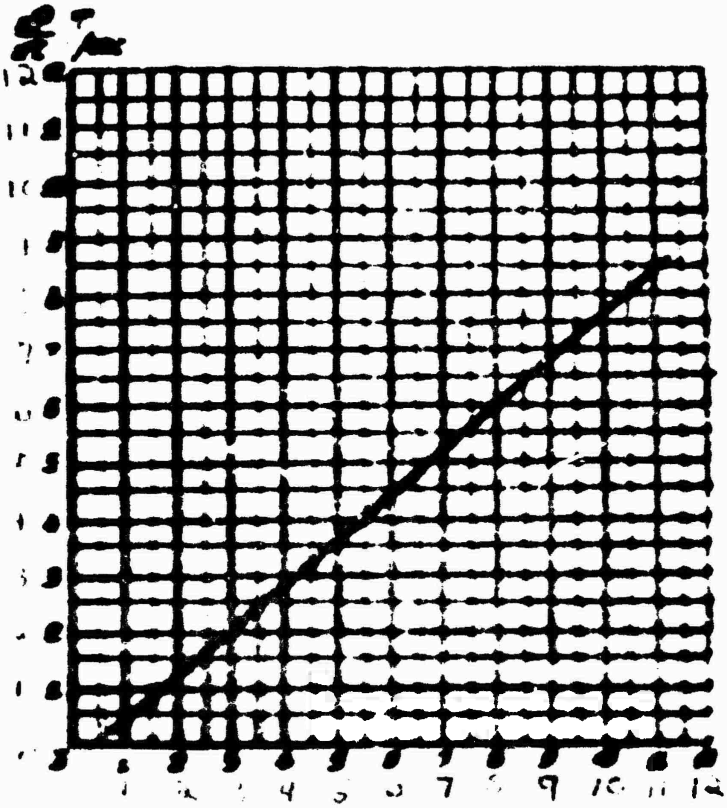


Fig. 13. Working Graph for Relationship of Criterion Reflecting Icing Rate N, cm/hr, and Actual Icing Rate $dP/d\tau$ in tons/hr for Type MFT Vessel.

Key: a. $dP/d\tau$, tons/hr

b. N, cm/hr

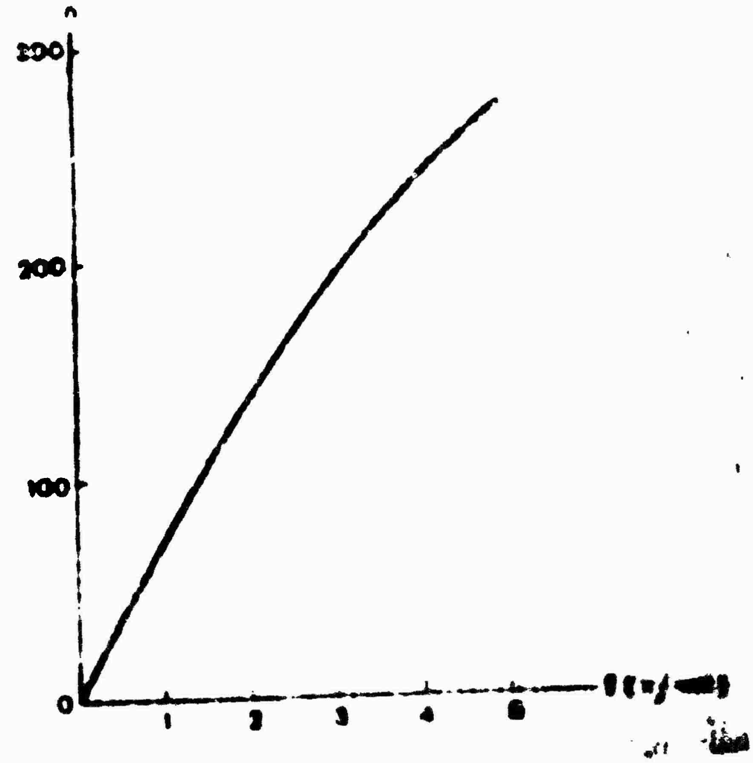


Fig. 14. Curve Showing Dependence of Icing Rate of Ships of MFT Type and of Ships Having Similar Dimensions, on n-Value.

Key: a. (? value not legible/hr).

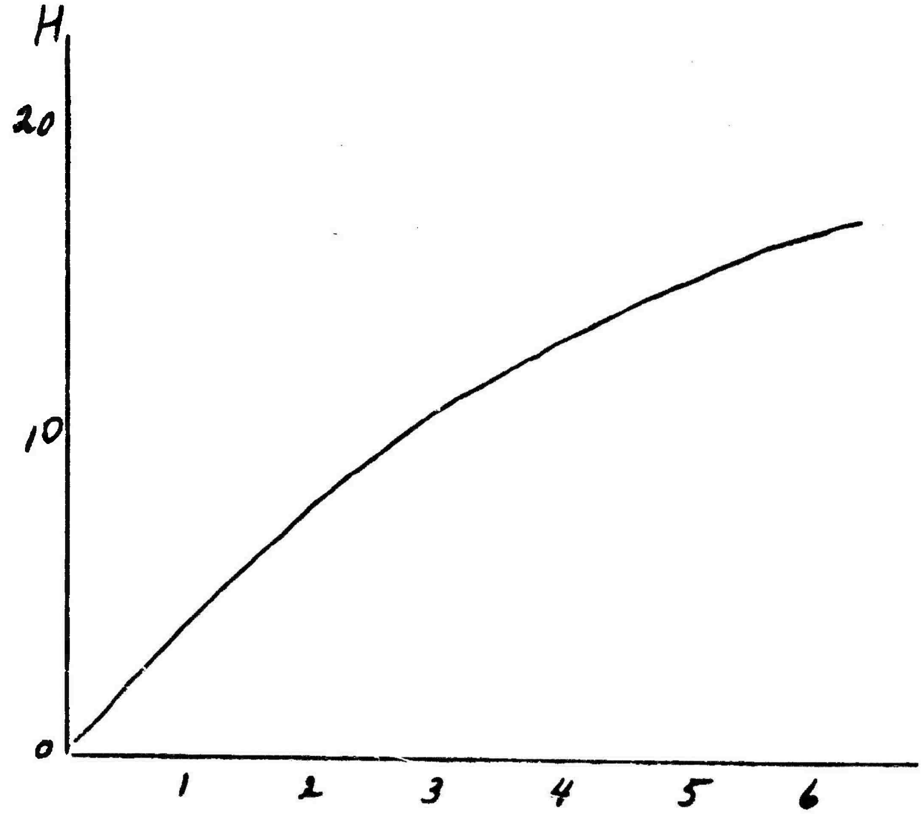


Fig. 15. Relationship Curve for Weight of Ice on MFT vs Average Ice Thickness on Woodrail (in 1 hour).
Key: a. H [? -symbols not legible]

b. [? not legible.]